Maximize then optimize the reduction efficiency in a kraft recovery boiler

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First presented at the Western Canada BLRBAC meeting in Vancouver in April 2014

Keywords: BOILER; RECOVERY; DESIGN; REDUCTION; COMBUSTION; AIR; PRIMARY; EFFICIENCY.

ABSTRACT

The key determinant of reduction efficiency in kraft recovery boilers is the temperature at the char bed. At least one commercial system optimizes the air distribution and adjusts the liquor temperature and pressure in order to maximize the temperature at the char bed and thus optimizes the reduction efficiency. This system is quite expensive and has a payback time of approximately two years. In contrast, a two-wall primary air system has a payback time of the order of six months and is a low-cost method of increasing the effectiveness of the primary air system by improving gas mixing which results in better combustion, a hotter lower furnace, higher reduction efficiency, higher thermal efficiency, less carryover, fewer dregs and a quieter dissolving tank. More than 15 years of operating experience with two-wall fully-opposed primary air jets have been accumulated at various mills and all the boilers tested have exhibited higher temperatures in the lower furnace and a stable char bed. Further improvements have been demonstrated in a short trial with two-wall partially-interlaced primary air jets on a large unit.

A short boiler trial, if desired, is sufficient to confirm that two-wall primary air will improve the reduction efficiency.

The paper concludes that two-wall primary air should be employed to maximize the reduction efficiency and then a commercial system for optimizing the reduction efficiency should be installed.

Application

The two-wall primary air technique is readily implemented in all kraft recovery boilers in which the primary air is directed just a few degrees below the horizontal and can be applied to boilers with steeply-sloping ports if the ports are fitted with inserts or if they are rebuilt to direct the primary air jets a few degrees below the horizontal.

Introduction

A pulp mill is a complex entity whose over-riding role is to make money for the owners. Every mill project, therefore, must either make money, or save money.
**Char-bed and Lower-furnace Temperature**

Table 1 presents the reduction efficiency and the corresponding boiler loads and char-bed temperatures extracted from the Paprican report (3) on the operation of RB4 at Crofton in February 2003. The boiler was operating with 56 of the sidewall ports closed, using the register dampers, basically running with almost all the combustion air from the front and rear walls, in a two-wall fully-opposed primary air configuration.

<table>
<thead>
<tr>
<th>Firing rate lb ds/d</th>
<th>3,400,000</th>
<th>4,000,000</th>
<th>4,500,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Char bed temp. C</td>
<td>939</td>
<td>980</td>
<td>1008</td>
</tr>
<tr>
<td>Red. Efficiency, %</td>
<td>88.8</td>
<td>92.5</td>
<td>93.4</td>
</tr>
</tbody>
</table>

These data in Table 1 confirm the conventional wisdom that the reduction efficiency increases with boiler load and the char bed temperature. However, the smelt does not “see” the boiler load – the smelt only experiences the char-bed temperature. The char-bed temperature determines the reduction efficiency.

Pantsar (4) reported that, after modifications to the combustion air and liquor delivery systems and the implementation of computer control in a boiler in Finland, the reduction efficiency increased from 90% to 95% when the temperatures in the lower furnace increased by 150 C. This is a broad-brush observation, but, clearly, depending on the point on the curve of reduction efficiency as a function of lower-furnace and char-bed temperature, the reduction efficiency is very sensitive to changes in temperature at the char bed – see Figure 1.

Typically, reduction efficiency at full load in various boilers varies from the high 80s to the mid 90s; however, it might be 92% at MCR, but perhaps only 85% at 75%MCR. A low reduction efficiency can be improved, but it should be measured regularly as a reminder to strive to improve it.

**Char-bed Shape and Control**

A stable char bed improves the reduction efficiency, but the char bed shape may change many times during an 8-hour shift and adversely affect the reduction efficiency. The shape changes for many reasons, such as:

- changes in liquor solids
- changes in dead load
- liquor-nozzle fouling
- boiler load
- operator inattention.

The char bed is shaped by the primary air jets from all four walls. These air jets throw up a char rampart which deflects the air jets upwards, creating a central gas column in the furnace. This upward-moving column of gases is further reinforced by the interference of the air jets from adjacent wall, in the corners of the furnace. This gas column promotes carryover of particulate up into the upper furnace and has been extensively modelled both physically and mathematically.

The char rampart thus created prevents the primary air from reaching the centre of the hearth, where a low-temperature zone exists on the char bed, especially in large furnaces. This low-temperature zone of poor combustion generates CO, TRS and H₂S and lowers the reduction efficiency.

Further, Tavares et al. (5) showed that there was twice as much fume generated from a char bed having uneven temperatures than from a bed with even temperatures.

Many older recovery boilers with two-level air have added another level of air just above the primary air. The total amount of combustion air is maintained, so this additional level of air is provided with its air by reducing the amount of primary air and the amount to the air level above the liquor guns. In order to maintain the air velocity from the primary air ports, selected primary air ports are blocked around the periphery of the furnace. The central gas column is still created by the primary air jets from the four walls, but it is somewhat weaker and it still promotes carryover.

Recovery furnaces are designed for 5-8% excess air, equivalent to about 1.3% O₂ by volume, dry. In practice, higher O₂ and the presence of CO indicate poor gas mixing. Also, the trend to smaller proportions of primary air often brings increased CO. To improve combustion and increase the temperature in the lower furnace, more-effective primary air is needed to provide better gas mixing and to bring the fireball down lower in the furnace, to utilize the expensive heating surfaces of the furnace more efficiently.
It is not sufficient to simply increase the primary air flow (and pressure) to increase the penetration of the primary air jets because the excess air increases and the thermal efficiency decreases; further, the carryover increases because the central gas column becomes more pronounced.

**Two-wall Primary Air**

For a full explanation of the two-wall primary air technique in its various configurations, see MacCallum (6).

If the same total quantity of primary air used in the four-wall system is introduced from two “active” opposing walls only, then the desired higher air-jet penetration is obtained with the higher-pressure, higher-velocity primary air; the same O\textsubscript{2} is maintained. Carryover is decreased because introducing the primary air from two walls allows the central gas chimney to spread out, so, with the same flue gas quantity in the larger chimney, there is about one-third of the original upward gas velocity and significantly less carryover. The carryover is proportional to the upward velocity to the power 2.3, thus with 66% lower upward velocity the carryover is reduced by about 90%.

So – if a boiler has excessive carryover, moving to two-wall primary air will greatly relieve the problem.

The larger air jets in the two-wall set-up have much greater momentum and entrain and burn combustible gases from the surrounding environment. Also, because the port velocity is higher, the ports stay cleaner.

These large jets from each register combine to form a powerful slab of primary air which blasts char horizontally and also carries oxygen in to the centre of the furnace, thus providing better, hotter combustion over the entire surface of the char bed, thus increasing the reduction efficiency.

The char is pushed by the large slabs of primary air into the centre of the furnace and, in the fully-opposed arrangement of primary air jets, the char forms a low ridge parallel to the active walls. Such a char bed is extremely stable and its shape changes very little.

RB4 at Crofton, BC, a large single-drum Alstom boiler, operated with two-wall fully-opposed primary air (2wp) from 4 December 2002 for just over four years until February 2007. 20 of the original 36 primary air ports on each sidewall were blocked with refractory and the associated port rodders were removed and placed in storage. Unfortunately, after four years, some of the refractory broke down and char entered a register and burned through. For reasons which are unclear, the blocked ports were unblocked and the boiler reverted to conventional four-wall primary air (4wp) and promptly experienced a deterioration in performance. The char-bed temperatures are displayed in Figure 4.

In Figure 4, there were 5 sets of temperatures in 9 data sets noted in telephone conversations with control room operators when 40 primary air ports were blocked with refractory during the 45 months that the boiler operated in this manner from May 2003 until February 2007. There were 43 sets of temperatures noted during the initial five months trial period from December 2002 until May 2003 when the air to 56 primary air sidewall ports was closed off using the register dampers. When the boiler reverted to 4wp with all the primary air ports open in February 2007, there were 18 sets of temperatures noted in the five months from February until July 2007.

Contrary to expectations, when the ports were blocked with refractory, there was a significant difference in the char-bed temperatures at the Left, Centre and Right focus points registered by the Quadtek camera. This spread is attributed to the small sample size.
Table 2 summarizes the experience on RB4 at Crofton, showing the increase in the mean char-bed temperatures, using the four-wall primary air (4wp) condition as the Base condition.

<table>
<thead>
<tr>
<th>Four-wall primary air – all ports open</th>
<th>56 sidewall ports</th>
<th>40 sidewall ports</th>
<th>Base</th>
<th>Base + 131 C</th>
<th>Base + 175 C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four-wall primary air – all ports open</td>
<td>dampered shut</td>
<td>blocked with refractory</td>
<td>Base</td>
<td>Base + 131 C</td>
<td>Base + 175 C</td>
</tr>
</tbody>
</table>

These increases are similar to the increase reported by Pantsar (4), following the boiler upgrade in Finland, mentioned above, but in the Crofton case, only a minor modification was involved to block off the selected ports.

No reduction efficiencies were noted by the author during the above periods, but it is clear that the significant increase in char-bed temperature must have resulted in an increase in reduction efficiency.

With a hotter lower furnace, the liquor temperature can be reduced slightly. More of the larger droplets thus obtained reach the char bed and this also reduces the carryover.

Limitation of Fully-opposed Primary Air

From the very first trials of two-wall primary air, a fully-opposed arrangement had been adopted. Almost all of the trials displayed a char ridge at the centre of the furnace, parallel to the active walls. It was eventually recognized that this ridge could be eliminated if a partially-interlaced arrangement of the primary air was adopted.

Partially-interlaced Primary Air

In 1988, Sandwell Swan Wooster Inc. conducted a confidential study (7) which was funded by The BC Science Council, 12 pulp companies, the BC Ministry of Environment and Sandwell. Using a 1/12th scale physical model, two-wall primary air was found to reduce the upward velocity extremes in the furnace. Partially-interlaced air jets at the secondary level eliminated the chimney in the centre of the furnace and provided more or less “plug flow” upwards – that is, the upward-velocity extremes were more or less eliminated.

In 1992, MacCallum (8) described the development of partial interlacing and presented its advantages. It was not until several years later, however, that it was appreciated that partial-interlacing would also be advantageous at the primary elevation. The scavenging jets solved the problem of char piling in the corners. New patents were eventually obtained (9).

As noted above, a ridge of char has been observed in almost all of the boilers operating with fully-opposed primary air, as shown in Figure 5.

<table>
<thead>
<tr>
<th>Ridge of char</th>
<th>Scavenging jets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</table>

When a partially-interlaced arrangement of jets is adopted, with each large jet opposed by a smaller jet, as shown in Figure 5, the large jets can then penetrate beyond the centreline of the furnace and create a pattern of jets that minimizes the upward velocity extremes and minimizes carryover. There is no ridge of char and the bed is flat.

A significant advantage of the arrangement is that the air jets can be introduced from the front and rear walls when the smelt spouts are on the front or rear walls, or from the sidewalls when the spouts are on one or both sidewalls, without significantly affecting the zone above the primary air.

Partially-interlaced Primary Air Experience

In the fall of 2011, a large Metso boiler operated for several days in a trial with a preliminary arrangement of two-wall partially-interlaced primary air and similar improvements were demonstrated. During the trial, only the primary air was adjusted – neither the secondary air nor the tertiary air, nor the liquor-spraying systems were altered. The furnace was 11 m square and the char bed was flat and well controlled, as shown in Figure 6.

<table>
<thead>
<tr>
<th>Figure 6 - Large Metso furnace operating with partially-interlaced primary air</th>
<th>Ridge of char</th>
</tr>
</thead>
</table>
air pressure of 25-40 mm w.g. was maintained in the sidewall ports to ensure that char did not enter any of the sidewall registers. The large jets from the active walls were created with windbox pressures of 90-100 mm w.g. and the small jets were created by pressures of about 50 mm w.g. The primary air was 25% of the total combustion air and the CO was around 20 ppm during most of the trial, with one spike to 50 ppm and another to 60 ppm.

Significantly, the char-bed pyrometers recorded a mean temperature approximately 50 C higher with partially-interlaced primary air than with the conventional four-wall primary air.

The operators noted a more stable bed, with a ridge at the centre of the char bed, parallel to the active walls.

High-solids Firing and Partially-interlaced Primary Air

High-solids firing seems to be the ultimate in modernizing a recovery boiler. However, it is still difficult to operate with low O₂ because of the limitations of conventional four-wall primary air. Partially-interlaced primary air can be expected to improve this situation.

Operating Experience with Two-wall Primary Air

More than 15 years of operating experience with two-wall fully-opposed primary air jets have been accumulated at various mills, as shown in Figure 8. All of these boilers have the primary air ports directed at about 5 degrees downwards, except the boiler at Mackenzie which was a B&W boiler with steeply sloping primary air ports.

In several extended trials, char entered one or more primary air registers. For example, this happened on RB1 at Northwood, after some 14 months of operation with two-wall primary air; two-wall primary air was immediately stopped on both boilers.

The same sort of mishap occurred at Skookumchuck after about six weeks of a trial, so the trial was discontinued.

Since those early trials, we have emphasized the hazards and have recommended only short-duration trials with the ports dampered.

Implementation of Two-wall Primary Air

For effective and safe operation with two-wall primary air, the selected ports must be blocked, either with refractory or with inserts – and this requires a shutdown.

Although shutdowns may be hectic, the primary port work can be prioritized to realize substantial savings. The blocking of the ports is a relatively simple modification to accomplish a short payback time of very few months.

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Small Boiler experienced Temperature Increase of More than 60 C with Preliminary Partial Interlacing

A short trial of the small CE boiler at The Pas in May 2013 produced very interesting results. The original unit had only two elevations of combustion air; a third elevation of air was installed just above the original primary elevation in 2011.

The boiler has only three primary air registers on each sidewall, compared to six registers on each of the front and rear walls. The three spouts are on the front wall.

Obviously, when this boiler is operated with 2wp, much less air is available to transfer from the sidewalls to the active front and rear walls, than in a boiler like RB4 at Crofton, where there were nine registers on each sidewall and only five on each of the front and rear walls.

Nevertheless, when the three sidewall registers were dampered down to 10 mm w.g. and the front and rear registers were operated with 80 mm w.g., the bed cameras recorded a temperature increase of 113 F (63 C). It should be noted also, that for the first three days of the trial, very little liquor was available and the boiler was running at about 80% load. The temperature increase with 2wp would probably have been greater at full load. Again, this temperature increase would have been accompanied by an increase in the reduction efficiency.
**Why is Two-wall Primary Air not Universally adopted?**

With all the positive experience of 2wp, the question arises: why is the system not employed on every boiler?

The answer lies partly in our “herd mentality” - no one likes to be first into the water when the crocodiles are lurking! Also – can the boiler manufacturers be wrong? Obviously all these primary ports must be needed.

It would appear that the advantages and cost savings must be better explained.

**Advantages of 2wp and its Effect on Reduction Efficiency**

The main advantages of two-wall primary air are that the arrangement:

1. improves gas mixing at the primary elevation and allows the boiler to operate with lower excess air and less CO, thus improving thermal efficiency
2. increases the temperature in the lower furnace and improves reduction efficiency
3. improves char bed control
4. reduces the amount of fume at any given mean charbed temperature by levelling out the temperature across the surface of the char bed
5. allows good operation with a low char bed which minimizes burndown time prior to a shutdown
6. minimizes the risk of blackouts
7. minimizes spiking of TRS and SO₂
8. by bringing the fireball down, 2wp utilizes the furnace heating surfaces more fully, lowers the furnace exit gas temperature and reduces the stickiness of the particulate carried over into the pendent heating surfaces in the upper furnace
9. provides smooth flow of smelt, thus minimizing the risk of explosions in the dissolving tank
10. minimizes carryover by spreading out the flue-gas chimney over the plan area of the furnace and minimizing the upward-velocity extremes
11. reduces dregs
12. eliminates many air ports and port rodders from the inactive walls and simplifies boiler operation
13. can use fewer, larger ports on the two active walls in a new or rebuilt furnace
14. allows the port-rodding frequency to be reduced on the active walls because the higher air velocity in these ports keeps the ports cleaner
15. employs fewer primary air ports and associated equipment, so the capital cost of a new or rebuilt boiler is lower.

By the simple expedient of blocking selected air ports on the inactive walls, the technology can be applied to all recovery boilers where the primary air is directed slightly downwards, say 5 degrees below the horizontal.

On every boiler, the reduction efficiency varies all the time. Using two-wall primary air, the reduction efficiency is increased over the entire load range.

Figure 9 below shows how 2wp moves the temperature range at the char bed farther up the temperature curve than the range created by a conventional four-wall system.

![Figure 9 – Reduction Efficiency as a Function of Temperature](image)

In most boilers with relatively high reduction efficiencies at full load, only a small increase in reduction efficiency will be observed at the high loads when the boiler operates with two-wall primary air, but at low loads the improvement will be greater and thus the cost savings will be significant.

**Furnace Rebuilds and Air-system Upgrades**

Conventionally, few changes are made to the four-wall primary air system when the furnace is rebuilt. The cost savings are considerable if two-wall primary air is adopted. 2wp offers better operation with less equipment.

The experience with 2wp is extensive and consistent and a boiler trial with dampered primary air registers is not really necessary. However, a short trial may be conducted at any time over the period of a few days. It is essential, however, that the trial is properly supervised and that all the operators understand the intent of the trial.

**Operating Cost Savings**

The order-of-magnitude operating cost savings which result from the use of two-wall primary air are shown in Table 3:

<table>
<thead>
<tr>
<th>Item</th>
<th>Operating cost Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction efficiency increase</td>
<td>$300,000 to 400,000</td>
</tr>
<tr>
<td>Thermal efficiency increase</td>
<td>70,000 to 150,000</td>
</tr>
<tr>
<td>Fewer dregs to landfill</td>
<td>?</td>
</tr>
<tr>
<td>Less carryover</td>
<td>?</td>
</tr>
<tr>
<td>Less sootblowing steam used</td>
<td>?</td>
</tr>
<tr>
<td>Lower maintenance on port rodders</td>
<td>?</td>
</tr>
<tr>
<td>Less risk of dissolving tank explosions</td>
<td>?</td>
</tr>
<tr>
<td>Order of magnitude op. cost savings</td>
<td>$370,000 to $550,000</td>
</tr>
</tbody>
</table>
Maximize then Optimize the Reduction Efficiency

Based on Table 3 above, it is clear that by NOT operating the recovery boiler with two-wall primary air, the mill is ignoring a cost-saving opportunity. As indicated, a reduction efficiency increase of 2-3% alone saves US$300,000 to 400,000 annually on a 1000 t/d recovery boiler.

On the basis of the investment costs and the payback times, the logical sequence is, first, to operate the boiler with two-wall primary air since the payback time is of the order of a few months, then second, install a reduction efficiency control system to optimize the reduction efficiency. The payback for the control system could be of the order of two years.

Acknowledgements

The author wishes to acknowledge that Jeff Butler's papers, quoted above, bring our attention to the Metso system for optimizing reduction efficiency and the significant operating cost savings that are obtained when the reduction efficiency in a recovery boiler is increased. Further, Bob Ericksen's efforts to recover more information at the Catalyst Paper mill in Crofton, BC and the interest displayed by Blair Rydberg at Tolko, The Pas Operations, are much appreciated.

References

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