Operating Experience with Plants with High Steam Parameters

Michael Mück

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Waste to energy plants had a clear defined task: *The safe disposal of waste*. Energy was a by-product and in the 60s and 70s the energy was dissipated in the atmosphere [17].

After the first waste incineration plants were built with moderate life steam parameter, the energy business asked for higher efficiency and changed the view from burning waste to energy production. Requirements from the legislative authority like *R1-factor* did their part. But not only this item was a driver. Requirements from existing power stations where the waste fired boiler is just a supplier of steam, high benefit for electrical output or the pre-sorting of waste are drivers for high steam parameters.

In the meantime, a lot of articles where published to describe:

- benefit and impact of high steam parameter,
- experience with high steam parameter plants,
- corrosion mechanism,
- realised modifications and material tests on plants, and
- benefit of retrofit measures.

This technical paper has the objective to summarize the different influences why high parameters are chosen for some plants. The technical consequences for realising the boiler concept and what are the challenges and feedback during operation.

An analysis of the feedback from different plants build by Steinmüller Babcock Environment according to life time of boiler parts, availability and maintenance costs may give an answer to the question, which parameter are promise the best results.

1. Thermodynamic background

*Increasing of efficiency is on everyone lips* like stated in several reports and presentations [2, 5, 6, 17, 20]. Main reason is the higher economic pressure like increase of energy and maintenance cost and lost money by outage.

Higher efficiency is influenced by:

- efficiency of the waste fired boiler including the flue gas system, and
- efficiency of the water steam cycle.

Like described in [2, 17, 23], the boiler efficiency can be influenced by:

- combustion air ratio and air preheating,
- good burn out quality,
- maximum use of heat out of the flue gas,
- reducing of losses,
- optimising of combustion control for a constant operation and
- optimising of start up and shut down processes.

On the other hand, the total efficiency of a plant is depending on:
• efficiency of the boiler,
• steam parameter,
• condensate parameter and cooling system,
• efficiency of the steam turbine,
• using of low pressure steam for combustion air preheating, condensate and feed water preheating, and
• possible use of multi stage steam super heating.

A possibility to visualise this matter is shown in the following diagram.

Figure 1: Measures to increase plant efficiency


In Figure 1 you can find the following message: As greater the area inside the marking, as higher the energy output.

Some of the measures are influencing each other, for example the use of flue gas for condensate reheating and the use of low pressure steam for condensate preheating.

Increasing of efficiency is limited and this as well by risks according to the size of a plant, the availability and costs of material as well as the silent risks like corrosion and fouling. Higher efficiency has its costs as well as risks [17] and efficiency and economic benefits on the other hand.
1.1. Theoretical influence of high steam parameter

In several publications [5, 6] the design concepts of waste fired boilers are explained. The conclusion is more or less, that the parameter 40 bar/400 °C builds an optimum regarding availability, outage time and maintenance costs and is the basis for further developments.

In [5] a variation of the steam parameter from 40 bar/400 °C to 65 bar/440 °C, 74 bar/480 °C and up to 90 bar/500 °C was evaluated.

For high parameter a design is shown with a super-heater placed in the second pass (radiation part). The conclusion of this comparison is shown in the following table:

Table 1: Comparison of different steam parameters according to steam flow, efficiency, heat surface, size and electrical output

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Unit</th>
<th>Basis 40 bar/400 °C</th>
<th>1 65 bar/440 °C</th>
<th>2 74 bar/480 °C</th>
<th>3 90 bar/500 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>steam flow</td>
<td>t/h</td>
<td>69.76</td>
<td>68.32</td>
<td>66.23</td>
<td>65.53</td>
</tr>
<tr>
<td>boiler efficiency</td>
<td>%</td>
<td>82.00</td>
<td>82.00</td>
<td>82.00</td>
<td>82.00</td>
</tr>
<tr>
<td>heating surface total</td>
<td>m²</td>
<td>7,347</td>
<td>8,053</td>
<td>9,119</td>
<td>8,985</td>
</tr>
<tr>
<td>deviation in the heating surface</td>
<td>%</td>
<td>-</td>
<td>+ 10</td>
<td>+ 24</td>
<td>+ 22</td>
</tr>
<tr>
<td>deviation in the boiler length</td>
<td>%</td>
<td>-</td>
<td>+ 2</td>
<td>+ 5,2</td>
<td>+ 2,6</td>
</tr>
<tr>
<td>turbine power</td>
<td>MW</td>
<td>14.47</td>
<td>15.1</td>
<td>16.04</td>
<td>16.35</td>
</tr>
<tr>
<td>gross electrical efficiency</td>
<td>%</td>
<td>23.00</td>
<td>24.00</td>
<td>25.50</td>
<td>25.90</td>
</tr>
</tbody>
</table>


Figure 2: Comparison of amount of heat surface (of different types) depending on the steam parameter

The following results are pointed out:
- over proportional increase of super-heater surface with similar part load behaviour,
- more boiler house length necessary, and
- higher cost for maintenance of super-heater.

Especially the increase of electrical efficiency for the last step from 74 bar/480 °C to 90 bar/500 °C with 0.4 %-points is quite small related to the invest and maintenance costs [5].

As well [6] it is pointed out, that parameter of 500 °C live steam temperature are only reachable, when the flue gas temperature is above 650 °C to make sure, that the temperature difference for a basic fouled boiler is sufficient as well.

Steam temperature and pressure are mostly in relation to each other. Related to the standard parameter 400 °C/40 bar the tendency and influence of different combinations to the electrical power is shown in Figure 3.

![Figure 3: Tendency of difference in electrical power depending on the steam temperature and pressure](image)

1.2. Full cost evaluation

All this publications are more or less based on theoretical considerations. Additional investigations [14] try to take into consideration:
- additional costs for Inconel,
- additional super-heater costs,
• exchange costs for super-heater,
• costs for super-heater replacement,
• costs of additional down time, and
• revenue assumptions.

This seems to be a more detailed way to evaluate the real benefit of different parameters as well the calculation is based on figures which can be different from plant to plant.

Table 2: Power output versus steam parameter (Case study)

<table>
<thead>
<tr>
<th>Variant</th>
<th>Design parameter</th>
<th>Additional inconel costs compared to base variant 400/40</th>
<th>Additional super-heater cost compared to base variant 400/40</th>
<th>Frequency of super-heater exchange</th>
<th>Cost of super-heater replacement</th>
<th>Cost of additional down-time</th>
<th>Difference in power production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400/40</td>
<td>-</td>
<td>-</td>
<td>15</td>
<td>0.9</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>425/50</td>
<td>1.6</td>
<td>0.9</td>
<td>11</td>
<td>1.1</td>
<td>0.52</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>450/60</td>
<td>3.2</td>
<td>2.1</td>
<td>7</td>
<td>1.65</td>
<td>0.54</td>
<td>1.62</td>
</tr>
<tr>
<td>4</td>
<td>480/70</td>
<td>4.8</td>
<td>3.2</td>
<td>4</td>
<td>2.2</td>
<td>0.56</td>
<td>2.13</td>
</tr>
</tbody>
</table>

To get a realistic picture, it is important not only to see the benefit of power production. On the other hand other factors need to be evaluated, like shown in the table above:

• annual operating hours and tonnage per line
• own consumption
• project period and real discount rate
• boiler efficiency
• turbine efficiency
• NPV factor
• power sale price
• power value EUR/year
• gate fee
• invest costs
• maintenance costs/Exchange rate
• length of downtime period.

This leads to the evaluation of the Net present value (NPV). This measure accounts the time value of money. It provides a method for evaluating and comparing capital projects or financial products with cash flows spread over time.
Related to the plant condition in the above mentioned project the result for the highest NPV is a realisation with steam parameter of 50 bar and 425 °C.

2. Corrosion mechanism and influence parameter

2.1. Mechanism and parameter

Corrosion mechanism is a wide and complicated issue, influenced by a large number of parameters and mechanism. Since the focus of waste to energy plants is not anymore only on burning waste, efficiency and availability are important issues, as well as outage time and maintenance costs.

In literature can be found a lot of theoretical and practical articles which give an overview about these matters.

Corrosion attack from the flue gas side has the most important economic influence of all corrosion damages [20]. Related to a life time of a boiler pipe of ten years, corrosion rates of 0,025 mm/1,000 operating hours are moderate, but related to super-heater tubes, as well rates of 1 mm/1,000 h are given [20].

The nature of corrosion is characterised by three principle difficulties [20]:

- Just a local limited corrosion attack can lead to a break in the tube and can lead to damage and risk.
- It is not possible to monitor the complete heating surface during operation; as well covered areas cannot be reviewed.
- Parts of the heating surface are in the middle of a bundle and not reachable.
- Corrosion is influenced by thermal, chemical and mechanical reasons which are in interaction or can be in overlay. As well the reaction kinetic properties are from main importance. As a result, corrosion is a sum or potentiated effect of single influences. This leads to the fact, that corrosion effects cannot easily be generalised and transferred.

Details and explanations are explained in various presentations [1, 8, 12, 18, 19, 20, 21, 22, 24, 25, 26] about the mechanism and the effects. A curios matter is the behaviour of the corrosion rates during operating time, as shown in the following figure.

![Corrosion rate vs. Operating time graph](image)

**Figure 5**: Dynamic of corrosion at super-heater tubes (example from existing plant)


This figure as a result of a waste to energy plant shows, that especially with clean pipes the corrosion dynamic is different than with a fouling layer. The mechanism inside the fouling and as well the influence to high temperature chlorine corrosion is very complex.

Other behaviours, where corrosion ratios are going up and down depending on waste quality are seen as well. This makes it very difficult to estimate a life time of the heating surface and corrosion risk.

The corrosion of evaporator heating surfaces follows other mechanism. Different heat flows, temperatures and velocities in the area of the evaporator walls have an influence on the corrosion. The pipe edges are a preferred place where the mixture of different flue gas temperatures leads to precipitation of saturated salt loads. [20]
In general different corrosion mechanism and phenomena can be pointed out:

- high temperature chlorine corrosion,
- molten salt corrosion,
- corrosion by salt solution and dew point, and
- erosion corrosion.

The corrosion mechanism, as well the chemical, mechanical and thermal influence factors, are direct or indirect influenced by the fuel characteristic, the combustion and the temperature dissipation in the flue gas. This matter is quiet complex and shows that a single comparison of corrosion behaviour is not as simple as it seems.

The following figures show the influence of the flue gas temperature and the heating surface wall temperature related to the corrosion ratio.

The figures show the principal trend of corrosion ratio depending on wall and flue gas temperature.

In contrast to the convection heat surfaces, the radiation part can be characterised by different parts of boiler passes, split into corrosion zones.
Figure 7: Corrosion rate as function of flue gas temperature (measurement of existing plant with tube temperature of 430 °C)


Figure 8: 3D-Model of corrosion diagram with lines of equal corrosion rates

The sketch above shows the three parts of the radiation heating surface with different characteristics. S1 with restricted heat transfer with respect residence time requirements, S2 with high temperatures and influences from velocity and fouling related to corrosion behaviour. S3 is important to cool down the flue gas and is also influenced by fouling in relation to corrosion aspects. Especially in the area where the flow direction changes and which is influenced by cleaning systems and their cycles, the corrosion dynamic will be different and can lead to high losses of wall thickness [20]. The chosen steam pressure and related to this the evaporator temperature can influence the corrosion ratio as well. Protection by Inconel reaches its limit in this case, like shown in a later evaluation.

Molten salt corrosion and high temperature chlorine corrosion are the main mechanism for super-heater surfaces. The chosen live steam temperature is the main driver and is characterised in the so called corrosion diagram which is described later. By separating the salts dissolved in the exhaust gas, by the significantly increased flow rates of the exhaust gas into the bundle and by the very large surface, contact heating surfaces can act as filters which fix part of the particle charge of the exhaust gas in the form of linings and create the basis for the corrosion attacks [20]. The content of the flue gas, temperature level of the flue gas and tube, the heat flux, as well as the material have the highest impact.

The increasing of corrosion load is also influenced by legal requirements and economical reasons. As answer different protection developments from ceramic material to Inconel layers were developed and tested with different success. In additional to refractory in the combustion chamber and lower part of the first pass, Inconel layer with Alloy 625 and 686 are used and approved for radiation pass as well as for super-heater bundles, but also reach their limit. Several other layer materials are available on the market.
Further investigations come to the result, that the corrosion attack starts from a tube temperature of 380 °C related to the fuel quality of the tested plant (600 °C flue gas temperature) [21]. As well the comparison between 400 °C steam temperature and 450 °C steam temperature shows a significant increase of corrosion attack like shown in the following figure.

![Corrosion rate of different protection layers/pipe materials](image)

Figure 10: Corrosion rate of different protection layers/pipe materials


The evaluation of the influence of different protecting materials comes to the result, that it is possible to reduce the corrosion rate [21].

By studying the different articles and experiences, it can be pointed out that the corrosion which leads to a damage is often just a small area caused by tup-shaped corrosion and is not related to the whole pipe or heating surface part (Figure 11) [24]. Unfortunately the boundary conditions are often outside the corrosion area of the corrosion diagram.

To paint a picture of the partly very individual corrosion processes, different systems to monitor and evaluate the mechanism are developed. An example is described in [24] by a sonde which transfers the corrosion rate into a flow of electrons. By this measurement the influence of material, fuel, flue gas and steam temperature can be evaluated.

It is pointed out, that in a long term test the influence of different parameters and the corrosion behaviour can be evaluated and used as basis for further improvements.

But also with balancing the material the corrosion phenomena can not be answered. So the Flingern'sche Corrosion Diagram was a good help for engineers to get a picture about the corrosion risk [1]. But like almost with simplified diagrams the risk is that
the interpretation gives place for misunderstanding. In [1] a context is been given between saturation concentration of various halogens, heat flux, surface temperature and flue gas temperature. As well the influence of velocity in the form of Aquikalore, the fouling influence to the surface temperature and the content of the flue gas is taken into account. Finally it is pointed out that also geometry and flue gas content has a major influence to heat flux and the corrosion as result.

![Figure 11: Measurements of wall thicknesses, estimation of development during normal operation and worst case](source)


![Figure 12: Chlorine content in the area of a boiler tube](source)

Figure 13: Modified corrosion diagram extended by velocity and chlorine content


Table 3: Chlorine in waste

<table>
<thead>
<tr>
<th>Mixed fraction</th>
<th>Composed of the analysis substance groups</th>
<th>Share of residual waste</th>
<th>Water content</th>
<th>Chlorine content</th>
</tr>
</thead>
<tbody>
<tr>
<td>fine waste</td>
<td>fine waste</td>
<td>12.6</td>
<td>28.7</td>
<td>0.25</td>
</tr>
<tr>
<td>middle waste</td>
<td>middle waste</td>
<td>11.6</td>
<td>49.7</td>
<td>0.48</td>
</tr>
<tr>
<td>organic</td>
<td>organic</td>
<td>14.1</td>
<td>61.3</td>
<td>1.1</td>
</tr>
<tr>
<td>paper, cardboard, catonage</td>
<td>paper, cardboard, catonages</td>
<td>10</td>
<td>21.9</td>
<td>0.59</td>
</tr>
<tr>
<td>synthetic materials</td>
<td>plastic packaging incl. foils</td>
<td>9.5</td>
<td>14.3</td>
<td>2.7</td>
</tr>
<tr>
<td>textiles</td>
<td>textiles shoes</td>
<td>5.2</td>
<td>12</td>
<td>1.01</td>
</tr>
<tr>
<td>composites</td>
<td>other composites</td>
<td>10.5</td>
<td>9.4</td>
<td>3.4</td>
</tr>
<tr>
<td>wood</td>
<td>wood</td>
<td>1.6</td>
<td>13.9</td>
<td>0.9</td>
</tr>
<tr>
<td>hygiene products</td>
<td>hygiene products</td>
<td>9</td>
<td>61.8</td>
<td>0.4</td>
</tr>
<tr>
<td>leather, rubber, cork</td>
<td>leather, rubber, cork</td>
<td>0.5</td>
<td>6</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Heat flux and flue gas flow are also the driving forces for corrosion and evaluated with measurements with a probe, as well calculated with FEM [8]. Heat flux leads the material flow out of gaseous chlorine and salts to the place of highest heat flux.

The balance of corrosion drivers like chlorine content around the fouling layer and the local flue gas composition and fly ash is depending on many parameters and can change immediately.

The picture above (Figure 12) also shows the increase of chlorine concentration in the fouling layer around a tube [26].

The flue gas velocity and chlorine concentration gives a wider range of corrosion potential like shown and implemented in the advanced corrosion diagram (Figure 13) [12, 25, 26]. This matter is mainly depending on the waste quality. Table 3 shows the weight range of chlorine content in different waste types and gives a picture of the difficulty to fix an individual influence to each plant. A general influence is pointed out in Figure 13.

2.2. Monitoring

Furthermore, a systematic optimisation of boiler parts by continued measurements, evaluations analysis can be the key to reduce maintenance costs caused by corrosion [22]. Predictive monitoring can help to reduce unplanned outages and shorten the revision time [19].

![Wall thickness vs. Operating hours](image)

**Figure 14:** Loss of wall thickness by continuous monitoring during life time (example of a existing plant)

Table 4: Monitoring and previous view of wall thickness and life time (example of an existing plant)

<table>
<thead>
<tr>
<th>Component</th>
<th>Position and height</th>
<th>Zero wall thickness mm</th>
<th>Operating time h</th>
<th>Minimum mm</th>
<th>Corrosion mm/1,000 Bh</th>
<th>Lifetime prognosis h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-heater 3</td>
<td>AGin + 17m</td>
<td>5</td>
<td>40,000</td>
<td>4.2</td>
<td>0.02</td>
<td>Replacement probably necessary at next revision</td>
</tr>
<tr>
<td></td>
<td>AGOut + 17m</td>
<td>5</td>
<td>40,000</td>
<td>4.2</td>
<td>0.02</td>
<td>Replacement probably necessary at next revision</td>
</tr>
<tr>
<td></td>
<td>AGin + 21m</td>
<td>5</td>
<td>40,000</td>
<td>3.2</td>
<td>0.05</td>
<td>Replacement necessary after 4 or more years</td>
</tr>
<tr>
<td></td>
<td>AGOut + 21m</td>
<td>5</td>
<td>40,000</td>
<td>3.7</td>
<td>0.03</td>
<td>Replacement probably necessary in 2-3 years</td>
</tr>
<tr>
<td></td>
<td>AGIn + 17m</td>
<td>5</td>
<td>80,000</td>
<td>4.3</td>
<td>&lt; 0.01</td>
<td>Replacement necessary after 4 or more years</td>
</tr>
<tr>
<td></td>
<td>AGOut + 17m</td>
<td>5</td>
<td>80,000</td>
<td>4.5</td>
<td>&lt; 0.01</td>
<td>Replacement necessary after 4 or more years</td>
</tr>
<tr>
<td></td>
<td>AGIn + 21m</td>
<td>5</td>
<td>80,000</td>
<td>4.1</td>
<td>0.01</td>
<td>Replacement necessary after 4 or more years</td>
</tr>
<tr>
<td></td>
<td>AGOut + 21m</td>
<td>5</td>
<td>80,000</td>
<td>4.4</td>
<td>&lt; 0.01</td>
<td>Replacement necessary after 4 or more years</td>
</tr>
</tbody>
</table>


The results of the example in Table 4, gives a good overview for further maintenance planning according to the different super-heater bundles. As well the results show that mostly just a partly exchange is necessary.

2.3. Plant feedback

From operator side a lot of single steps are possible to reduce corrosion attack. To point out the needs a survey of 183 waste fired boilers listed in ITAD shows to the following results as a feedback of 16 plants [4] (Figure 15 and 16):

- Most boilers (44 %) have a corrosion rate between 0,1 to 0,3 mm per year in the evaporator part. Approximately 20 % (3 plants) have much higher rates and a challenge to solve. Unfortunately no relation to steam parameter and material was possible.
- Most boilers (60 %) have a corrosion rate between 0,5 to >1,3mm per year in the super-heater part. Unfortunately, no relation to steam parameter and material was possible.

Nevertheless the above shown figures point out that the major focus with high corrosion ratios is in the area of super-heater and just a small number is related to the evaporator.
Figure 15: Corrosion ratio in evaporator


Figure 16: Corrosion rates in super-heater

3. Current status /design parameter of plants

Waste to energy plants are characterised by a limitation of the steam parameter caused by the *high temperature corrosion*. So the typical steam parameters are 40 bar/400 °C [17]. But in deviation to this there are various other plants with different steam parameters. The following part shows their operation experience.

3.1. Overview of plants in Germany

An overview of German waste to energy plants status 2005 is given in Figure 17:

![Figure 17: Steam parameter of 183 listed waste boilers at ITAD (2005)](image)


Table 5: Plants with high steam parameters until start up 2016

<table>
<thead>
<tr>
<th>Site</th>
<th>Temperature °C</th>
<th>Pressure bar</th>
<th>Supplier</th>
<th>Start-up year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hameln (Germany)</td>
<td>450</td>
<td>49</td>
<td>SBE (VKW)</td>
<td>1977 (K1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1983 (K2)</td>
</tr>
<tr>
<td>Düsseldorf (Germany)</td>
<td>500</td>
<td>90</td>
<td>SBE (VKW)</td>
<td>1980 (K6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lentjes: K4</td>
<td>1990 (K3 &amp; 5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1991 (K1 &amp; 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1995 (K5)</td>
</tr>
<tr>
<td>Oberhausen (Germany)</td>
<td>&gt;= 460</td>
<td>60</td>
<td>SBE (DB)</td>
<td>1985 (K4)</td>
</tr>
<tr>
<td></td>
<td>&gt;= 400</td>
<td></td>
<td></td>
<td>1997 (K1 &amp; 2)</td>
</tr>
<tr>
<td>Hempsted (USA)</td>
<td>443</td>
<td>60</td>
<td>SBE</td>
<td>1989</td>
</tr>
</tbody>
</table>
### Table 5: Plants with high steam parameters until start up 2016 – continuation

<table>
<thead>
<tr>
<th>Site</th>
<th>Temperature °C</th>
<th>Pressure bar</th>
<th>Supplier</th>
<th>Start-up year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stuttgart, Münster (Germany)</td>
<td>525</td>
<td>66</td>
<td>SBE: K26 (DB)</td>
<td>1994 (K26)</td>
</tr>
<tr>
<td></td>
<td>=&gt; 500</td>
<td></td>
<td>AE &amp; E: K21 &amp; 22</td>
<td>2006 (K21 &amp; 22)</td>
</tr>
<tr>
<td>Rüdersdorf (Germany)</td>
<td>420</td>
<td>90</td>
<td>SBE</td>
<td>2008</td>
</tr>
<tr>
<td>Naples (Italy)</td>
<td>500</td>
<td>90</td>
<td>SBE</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>=&gt; 470</td>
<td>=&gt; 80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ruhleben (Germany)</td>
<td>465</td>
<td>63</td>
<td>SBE</td>
<td>2012</td>
</tr>
<tr>
<td>Frankfurt (Germany)</td>
<td>500</td>
<td>60</td>
<td>Lentjes</td>
<td>2006</td>
</tr>
<tr>
<td>Paris Ivry (France)</td>
<td>470</td>
<td>96</td>
<td>CNIM (Martin)</td>
<td>1969</td>
</tr>
<tr>
<td>Milano (Italy)</td>
<td>440</td>
<td>52</td>
<td>Martin</td>
<td>2000</td>
</tr>
<tr>
<td>Amsterdam (Netherlands)</td>
<td>440 (=&gt;400?)</td>
<td>130</td>
<td>NEM (Martin)</td>
<td>2007</td>
</tr>
<tr>
<td>Brescia (Italy)</td>
<td>450</td>
<td>60</td>
<td>Ansaldo (Martin)</td>
<td>1998 (L1 &amp; 2)</td>
</tr>
<tr>
<td>Wheelabrator</td>
<td>500</td>
<td>86</td>
<td>Volund</td>
<td>1994</td>
</tr>
<tr>
<td>Falls PA (USA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Palm Beach (USA)</td>
<td>443</td>
<td>63</td>
<td>Volund</td>
<td>2015</td>
</tr>
<tr>
<td>Amager Bakke Copenhagen (Denmark)</td>
<td>440</td>
<td>70</td>
<td>Volund</td>
<td>2016</td>
</tr>
</tbody>
</table>

### Table 6: Plants with multi stage super-heating

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Pressure levels</th>
<th>Steam temperature °C</th>
<th>Rated thermal input waste MW</th>
<th>Rated thermal input gas/oil MW</th>
<th>Σ η el. net</th>
<th>η el. net waste</th>
<th>commissioning Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHKW</td>
<td>120</td>
<td>360 - 520</td>
<td>87</td>
<td>29</td>
<td>about 32</td>
<td>about 22</td>
<td>1997</td>
</tr>
<tr>
<td>Mannheim MK4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>external superheater with natural gas directly</td>
</tr>
<tr>
<td>MHKW</td>
<td>40</td>
<td>400 - 540</td>
<td>88</td>
<td>671</td>
<td>57</td>
<td>20</td>
<td>2003</td>
</tr>
<tr>
<td>Mainz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>external superheater with gas and steam cycle</td>
</tr>
<tr>
<td>AVI AZN</td>
<td>100</td>
<td>400 - 555</td>
<td>231</td>
<td>491</td>
<td>42</td>
<td>15</td>
<td>1997</td>
</tr>
<tr>
<td>Moerdijk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>external superheater &amp; reheater with gas and steam cycle</td>
</tr>
<tr>
<td>Bilbao</td>
<td>100/30</td>
<td>330 - 540/540</td>
<td>71</td>
<td>152</td>
<td>42</td>
<td>20</td>
<td>2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>external superheater &amp; reheater with gas and steam cycle</td>
</tr>
<tr>
<td>Andernach</td>
<td>70</td>
<td>400 - 525</td>
<td>51.4</td>
<td>8.6</td>
<td>about 22</td>
<td>&lt; 22</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>external superheater with waste oil / gas directly</td>
</tr>
<tr>
<td>AVI Amsterdam</td>
<td>130/40</td>
<td>440/320</td>
<td>2 x 93.3</td>
<td>-</td>
<td>&gt; 30</td>
<td>&gt; 30</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>internal reheater with live steam</td>
</tr>
<tr>
<td>Rüdersdorf</td>
<td>90/23.4</td>
<td>420/420</td>
<td>110</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>first pure waste reheater in boiler with grate combustion</td>
</tr>
</tbody>
</table>

Like mentioned before not all steam parameters are free chosen. Some plants are connected to an existing steam system of a conventional power station.

Table 5 gives an overview of plants with high steam parameters until start up in 2016. A number of plants are also out of this average range because the final super-heater are heated by external heat or other heating is used, like shown in table 6 [17].

3.2. Experience of plants with high steam parameters from literature

In various publications the experience with high steam parameters in waste to energy plants are described.

Mannheim [28]: The original design for the steam main line was 120 bar/520 °C, according to the existing steam line of the plant. In the meantime the parameters where decreased to 80 bar/480 °C.

Due to the experience with boilers from different ages, the economical question is one of the drivers to run a plant with benefit. The comparison between the older plants and modern plants is shown in the following figure.

![Figure 18: Comparison of old and new plants related to gate fee price](source)

It can be pointed out, that the year of building and the basis of experience have a main influence on the operating price per ton of waste. As well the optimisation and homogenisation of the fuel quality and the combustion control has a positive influence to the corrosion potential.

But finally the lowering of the steam parameters lead to a significant reduction of corrosion. Until this change evaporator heating surfaces with Inconel 625 in the combustion chamber reach a life time of less than 20,000 hours.

Further optimising have been realised like:

- modification of the grate,
- optimisation of refractory and protection layers,
- water blowers, and
- pitch of heat surface.

As result of this measures the availability is between 85 % and 88 %. Further steps related to grate and refractory are planned, combined with a pressure reduction to 65 bar.

The summery of this plant is, that with the higher steam parameter, the risk for high temperature corrosion and fouling increases disproportionately and if the effects are not manageable this leads to low availability and high costs – the plant is not efficient any more.

Plant between Germany and Netherlands [15]:

In the publication the design of the plant is described, it starts with a development of a concept for a steam outlet temperature of 460 °C/60 bar.

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>Unit</th>
<th>waste to energy plant 1</th>
<th>waste to energy plant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>steam parameters</td>
<td>°C/bar</td>
<td>460/60</td>
<td>400/40</td>
</tr>
<tr>
<td>gross efficiency η of the entire system</td>
<td>%</td>
<td>30.9</td>
<td>28.7</td>
</tr>
<tr>
<td>thermal power $P_{th}$</td>
<td>MW$_{th}$</td>
<td>2 x 76</td>
<td>2 x 76</td>
</tr>
</tbody>
</table>

Table 7: Boundary conditions for plant comparison

Table 8: Main design data in comparison with common design data

Table 9: Corrosion promoting mechanism in super-heater area

<table>
<thead>
<tr>
<th>Boundary condition</th>
<th>Mechanism</th>
<th>Countermeasure</th>
<th>Influence on boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>flue gas temperature upstream superheater</td>
<td>with increasing flue gas temperature increases the risk of corrosion</td>
<td>lowest possible velocity in the first boiler pass</td>
<td>larger heating surface through low temperature difference required</td>
</tr>
</tbody>
</table>
| ash cover on the superheater tubes        | ash cover on the superheater tubes increases the risk of corrosion (underlay corrosion) | • provide effective cleaning facilities  
• arrange impact protection upstream of the endangered tubes (svd) | none                                                                                            |
| flue gas velocity in the first pass       | with increasing speed in the first pass, the particle discharge increases in the boiler | lowest possible speed in the first boiler pass       | larger boiler dimensions                           |
| salinity in the ash cover                 | alkaline, alkaline earth and heavy metal salts increase the risk of corrosion | optimize fuel processing                            | none                                                                                            |
| steam temperature in superheater          | rising steam temperatures require higher material temperatures on the superheater tubes | • optimize superheater circuit (counter flow/ parallel flow)  
• coating the tube surface with wear-resistant materials | • size of heating surface varies according to circuit  
• operating temperature of coating materials to be noted |
| steam pressure in superheater             | higher minimum tube wall thickness required                               | none                                                |                                                                                                |


The Tables 7 to 9 show, that the concept has foreseen to lower the velocity, which is a first step to lower the corrosion risk. Upstream the super-heater the maximum flue gas temperature is with 700 °C very high but related to a part load behaviour. The final super-heater is in parallel flow and created with a wide pitch of 240 mm. The material is 13CrMo4-5 and the first four rows are cladded. During the operating time of 16,000 hours no damage takes place so an operating time of minimum two years is approved.

Frankfurt [9, 16]:

The plant in Frankfurt was renewed between 2003 and 2009 and the steam parameters of 500 °C/60 bar were kept because of efficiency reasons. Due to the experience with the old plant and cladded tubes in counter flow, the super-heater of the updated plant was designed in parallel flow and cladded with Alloy 686 (Figure 19).

Experience with corrosion effects are described like follows:

In the first rows in a height between 50 to 150 cm from the top, the corrosion rate is the highest. Further on (downstream) in the bundle the higher corrosion rate is more in the lower part of the tubes. This shows a correlation to the flue gas flow. As well tubes which are not in flue gas stream are more corroded. The operator was able to find a relationship between super-heater circuit and heat flux related to corrosion potential.
We protect and improve.
A plant life long. #AfterSalesService
Operating Experience with Plants with High Steam Parameters

Figure 19: Heat surface circuit


Figure 20: Average corrosion ratio during different operation period

Measurements during the outage shows corrosion rates in the cladded super-heater after 30,000 hours of operation in a range of 0.05 mm/1,000 h and 0.15 mm/1,000 h. The corrosion ratio decreases during operating time like also shown in Figure 20. But some pipes have to be changed earlier, especially when they protrude into the flue gas stream. Corrosion rates up to 0.3 mm/1,000 hours are possible.

After two years of operation in average approximately 15 % of the super-heater 3 tubes must be changed in both boilers and the super-heater 4 (final super-heater) was changed complete. After three years of operation nearly the same rate and after four years in average 4 %. These results shows that like described in Chapter 2, exchange rate/corrosion rate can be partly quite high and mostly not the full bundle is affected.

Further modifications where done after four years of operation. Due to the high inlet temperatures upstream the final super-heater the evaporator bundle upstream was increased by an approximately three times higher amount of heating surface to decrease the temperature by 60 K.

This modifications lead to a lower temperature and to a better temperature distribution upstream the super-heater and lower corrosion ratio like shown in Figures 21 and 22.

Figure 21: Measurement of flue gas upstream final super-heater


The effect of the modification is shown in the following Figure.
As well the positive effect of the modification is visualised in the comparison of line 11+12 (with modification) and line 13+14 (without modification).

**Stuttgart [7]:**

Another plant with high steam parameters and three lines is located in Stuttgart-Münster. 500 °C/61 bar are the steam parameters for the coal fired lines, as well for the waste fired one. The super-heater 3 and 4 are located in the second pass and protected by refractory (Figure 23).

The part of maintenance cost for this heating surface is approximately 61 % of the total budget. This forces the pressure to create solutions to reduce the maintenance cost.

The approaches for solving the problems have been:
- reduction of corrosion potential by optimising of combustion and heat transfer in 1st pass,
- protection of the super-heater pipes by refractory systems,
- cladding of the super-heater pipes,
- development of nano-ceramic protection layers at high loaded areas, and
- change of material (13CrMo44) for the first three pipe rows together with protection shields from Sicromal 20/10.

The optimising in the first pass leads to a reduction of flue gas temperature of approximately 60 K.
Figure 23: Corrosion diagram with position of super-heater


Figure 24: Cost comparison of cladding versus black material with refractory during operating time

Part of the evaluation and result was to create a picture of the different possibilities to optimise the maintenance costs with a long term view to the total costs like shown in Figure 24 and Table 10.

### Table 10: Technical and economic evaluation of the concepts studied

<table>
<thead>
<tr>
<th>Concept</th>
<th>Technical evaluation</th>
<th>Economic review</th>
</tr>
</thead>
<tbody>
<tr>
<td>cladding (622, 625, 686)</td>
<td>• depending on installation location</td>
<td>• use depends on the installation location</td>
</tr>
<tr>
<td></td>
<td>• service lives of up to &gt; 42,000 operating hours were proven</td>
<td>• cheaper than uncoated superheater heating surfaces</td>
</tr>
<tr>
<td>stainless steel</td>
<td>• results after a operation time were positive</td>
<td>• economy given</td>
</tr>
<tr>
<td></td>
<td>• further trials in planning</td>
<td></td>
</tr>
<tr>
<td>thermal spray coatings (different producers)</td>
<td>• in the final or pre-superheater the service life was &lt; one or two operation times.</td>
<td>an economic life has not been achieved.</td>
</tr>
<tr>
<td>thermal spray coatings with thermal densification</td>
<td>• so far, no sufficient service life</td>
<td>economic evaluation not yet possible</td>
</tr>
<tr>
<td></td>
<td>• further trials in planning</td>
<td></td>
</tr>
<tr>
<td>bulkheat heating surface (13crmo44) without refractory lining</td>
<td>service life of one operation time was reached</td>
<td>economy given</td>
</tr>
<tr>
<td>concrete delivery as superheater protection</td>
<td>• has not proven itself</td>
<td>economic not given</td>
</tr>
<tr>
<td></td>
<td>• no further use planned</td>
<td></td>
</tr>
<tr>
<td>compared to the standard mass faster radiant mass</td>
<td>• targets have been met</td>
<td>economy given</td>
</tr>
<tr>
<td></td>
<td>• time spent on blasting work reduced by 30%</td>
<td></td>
</tr>
<tr>
<td>compared to the standard mass significantly harder masses</td>
<td>system lives of &gt; 23,000 operating hours have been achieved</td>
<td>economy given</td>
</tr>
<tr>
<td>reduced and varied delivery with tubes</td>
<td>• it has proved its worth</td>
<td>economy given</td>
</tr>
<tr>
<td>refractory plates as superheater protection</td>
<td>• have proven themselves in the area with service life &gt; 30,000 operating hours</td>
<td>economy given</td>
</tr>
<tr>
<td></td>
<td>• try not finished yet</td>
<td></td>
</tr>
<tr>
<td>refractory plates as superheater protection</td>
<td>in the area of the inlet and outlet pipes, the service life was &lt; a operation time</td>
<td>an economically relevant service life has not yet been achieved</td>
</tr>
</tbody>
</table>


**Rüdersdorf/Rostock [10]:**

During the publishing of this article the plants in Rostock and Rüdersdorf belong to the same operator, so a comparison was possible. The plant in Rüdersdorf was designed for high electrical efficiency of approximately 30 % and has a concept with reheating of steam 420 °C/90 bar in a waste fired boiler. The plant in Rostock is design for standard parameter 405 °C/42 bar.
Table 11: Comparison of plant components

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Rüdersdorf</th>
<th>Rostock</th>
</tr>
</thead>
<tbody>
<tr>
<td>steam generation</td>
<td>boiler</td>
<td>natural circulation boiler with 4 vertical passes</td>
<td>natural circulation boiler with 3 vertical passes and 1 horizontal pass</td>
</tr>
<tr>
<td>wear protection/ basic equipment</td>
<td>1st pass: full cladding&lt;br&gt;2nd pass: cladding of superheater / reheater platens</td>
<td>1st pass: plate system, Ignition roof concrete, roof cladding&lt;br&gt;2nd pass: thermal coating</td>
<td></td>
</tr>
<tr>
<td>boiler cleaning</td>
<td>2nd pass: without&lt;br&gt;3rd pass: steamblowers&lt;br&gt;4th pass: without</td>
<td>2nd pass: Spray cleaning&lt;br&gt;3rd pass: Spray cleaning&lt;br&gt;4th pass: rapper</td>
<td></td>
</tr>
</tbody>
</table>


The comparison of the plants comes to the result, that independent from the boiler concept, the fuel quality, refractory/protection system, the combustion control and the velocities or inverse the pitches of the heat surfaces have as well an influence to fouling and corrosion behaviour. In the meantime some changes where realised to reduce the unplanned outages:

- widen pitch of evaporator grids and
- optimising cleaning system.

Related to the corrosion the following modification can be pointed out for the plant in Rüdersdorf:

- Due to a saturated steam temperature of 303 °C and in combination with the special fuel (RDF) and erosion, high corrosion rates are realised in the combustion chamber in the area of Inconel cladding. Thin-film panels were installed to protect the combustion chamber and parts of the 1st pass.
- Especially the final super-heater stages in the second pass are attacked by a mixture of erosion and corrosion. The flow situation inside the boiler, as well the high temperatures lead to a high ratio of lost wall thickness. Pipes which are not in line, as well the hotter pipes in upstream flow (steam outlet side meets high flue gas temperature) are mostly effected by corrosion. With the development of protective shells the situation was improved but not complete solved.

Also the wall thickness bows of the super-heater in the 3rd pass is reduced after 28,000 hours of operation.

The plant in Rostock had mainly problems with refractory in the combustion chamber and with the protection layer in the second pass. After 22,500 hours of operation the final super-heater shows a reduction of wall thickness in the first row which was changed in the next revision.

Summarised can be pointed out that the high efficiency concept in Rüdersdorf is opposite to the plant availability. Rostock is related to its normal parameter in an average range of corrosion potential, but with challenges according to refractory.
Operating Experience with Plants with High Steam Parameters

Naples, Bresica, Milano [27]:

The plant in Naples is designed for three lines with 113 MW\textsubscript{th} each and steam parameter of 90 bar/500 °C. Operation started in March 2009. The plant in Brescia is designed for three lines with 100 MW\textsubscript{th} each and steam parameter of 60 bar/450 °C. Operation started in March 1998. The plant in Milano is designed for three lines with 74 MW\textsubscript{th} each and steam parameter of 52 bar/425 °C. Operation started in February 2001. All three plants are operated by a2a ambiente. The results of the comparison of the plants are shown in the following table:

Table 12: Comparison of the plants Milano/Brescia/Naples

<table>
<thead>
<tr>
<th>Plant</th>
<th>Milan</th>
<th>Brescia</th>
<th>Naples</th>
</tr>
</thead>
<tbody>
<tr>
<td>steam parameter</td>
<td>425 °C / 52 bar</td>
<td>450 °C / 60 bar</td>
<td>500 °C / 90 bar</td>
</tr>
<tr>
<td>boiler type</td>
<td>3 vertical passes, horizontal pass for convection part</td>
<td>3 vertical passes, horizontal pass for convection part, vertical economizer</td>
<td>2 vertical passes vertical pass for convection part, vertical economizer</td>
</tr>
<tr>
<td>protection</td>
<td>1 superheater bank protected with Inconel 625</td>
<td>1 superheater bank protected with Inconel 625</td>
<td>radiation superheater 2+3 in 2nd pass protected with refractory; in the meantime change of SH to SH 1.05 with cladding</td>
</tr>
<tr>
<td>findings</td>
<td>no significant corrosion of superheater after 15 years of operation</td>
<td>acceptable corrosion/erosion (replacement of final superheater every 5 years)</td>
<td>refractory replacement 20 % each year, superheater every 4 years, 1 week longer outage</td>
</tr>
<tr>
<td>summary / total view</td>
<td></td>
<td></td>
<td>invest and maintenance costs higher than benefit of efficiency</td>
</tr>
</tbody>
</table>


It has to be pointed out, that the parameters in Naples are chosen because of a high political pressure on plant efficiency. For the first ten years an extraordinary high compensation for electrical output was promised. The situation changed completely at the beginning of this year.

3.3. Steam parameters of delivered plants

When you have a look to the waste to energy plants started operation until 2016, as shown in Table 5, you can see, that a certain number were built by Steinmüller Babcock Environment (SBE). The company offers a wide range of steam parameters by the delivered plants like Figure 25 shows.

Approximately 17 % of the plants built by SBE have higher parameter than the standard. The plant manufacturer studies and evaluates different steam parameters, and compares it with the results and feedback during operation.
In [11] a comparison of different boiler concepts is shown. The results in efficiency of waste to energy plants and the related gross power production are shown in Table 13.

The calculations were made on unified conditions for:

- waste composition (as the base solution),
- turbine outlet pressure,
- feed water temperature,
- turbine isentropic efficiency,
- condensate pre-heating,

as well as further parameters for the water/steam cycle.

The overall assessment of various stoker and boiler system solutions has to include – beside the energetic efficiency – the following aspects:

- operating performance,
- availability,
- costs for consumables,
- investment and maintenance, as well as
- plant outage time.

Figure 25: Plants built by Steinmüller Babcock Environment or predecessor companies
Table 13 also evaluates these criteria for each variant.

Table 13: Comparison base solution and variants 1-5

<table>
<thead>
<tr>
<th>Change compared to basis</th>
<th>Unit</th>
<th>Basis</th>
<th>Variant 1</th>
<th>Variant 2</th>
<th>Variant 3</th>
<th>Variant 4</th>
<th>Variant 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>reduced</td>
<td>flue gas</td>
<td>external</td>
<td>high</td>
<td>steam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>excess</td>
<td>cooler</td>
<td>superheating</td>
<td>steam</td>
<td>parameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>air</td>
<td></td>
<td></td>
<td>reheating</td>
<td>reheating</td>
</tr>
<tr>
<td>live steam temperature</td>
<td>°C</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>500</td>
<td>500</td>
<td>420</td>
</tr>
<tr>
<td>live steam pressure</td>
<td>bar</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>reheated steam temperature</td>
<td>°C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>420</td>
</tr>
<tr>
<td>reheated steam pressure</td>
<td>bar</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>flue gas temperature</td>
<td>°C</td>
<td>190</td>
<td>190</td>
<td>100</td>
<td>190</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>boiler outlet temperature</td>
<td>°C</td>
<td>190</td>
<td>190</td>
<td>100</td>
<td>190</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>excess air</td>
<td>%</td>
<td>60</td>
<td>39</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>boiler efficiency</td>
<td>%</td>
<td>86.5</td>
<td>87.7</td>
<td>92.6</td>
<td>87.7</td>
<td>86.5</td>
<td>86.5</td>
</tr>
<tr>
<td>boiler efficiency related to basis</td>
<td>%</td>
<td>100</td>
<td>101.3</td>
<td>107</td>
<td>100.5</td>
<td>100</td>
<td>100</td>
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<tr>
<td>gross electrical efficiency</td>
<td>%</td>
<td>26.4</td>
<td>26.6</td>
<td>28.4</td>
<td>29.7</td>
<td>30.2</td>
<td>29.9</td>
</tr>
<tr>
<td>gross electrical efficiency related to basis</td>
<td>%</td>
<td>100</td>
<td>101.1</td>
<td>106.8</td>
<td>112.6</td>
<td>114.6</td>
<td>113.3</td>
</tr>
<tr>
<td>electrical power production</td>
<td>0</td>
<td>0 to +</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>costs for consumables</td>
<td>0</td>
<td>0 to +</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>life time of membranwalls</td>
<td>1st pass without add. corrosion protection</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>life time of superheaters</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>costs for investment</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>continuous operation period</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

For the different variants presented, the following conclusions can be drawn:

**Furnace excess air reduction (Variant 1)**

The reduction in excess air should – depending on the combustion system – be done as far as possible in order to reduce the flue gas loss of the boiler. The membrane walls of the post combustion zone should be protected with Inconel 625 or with reduced flue gas temperature by recirculation. The reduction in excess air is equally possible for Variants 2 to 5 with similar effect and equivalent efficiency optimization.

**Temperature optimisation and additional flue gas cooling (Variant 2)**

The type of flue gas system dictates the opportunities of this variant. In case of a semi-dry FGC system heat used for evaporation of lime milk cannot be recovered. When a flue gas heat exchanger is installed for cooling down the flue gases, it has to be cleaned during operation and washing water could be captured. Compared to the base solution
this variant is a good alternative without constraints to plant operation and maintenance costs. The investment in additional heat exchanger surfaces is offset to extra earnings in generated electric power. A combination with Variants 3, 4 and 5 is possible without limitation for increase in efficiency.

**External super-heater (Variant 3)**

This variant requires approximately 14.5% of the thermal power from waste in addition from an auxiliary fuel as gas, oil or biomass. The additional fuel represents an important part of the plant operation costs. Compared to the base solution there are no constraints to plant operation, maintenance costs and availability. The tube wall temperature of the membrane is due to higher pressure compared to the base solution approximately 50 K higher and the 1st pass has to be protected with Inconel 625.

**High steam parameters (Variant 4)**

Higher power output of this variant goes along with lower availability due to higher inspection and maintenance requirements for the platen-type super-heaters. Higher steam pressure compared to the base solution is causes the necessity for additional Inconel cladding in the 1st pass.

**Intermediate reheat (Variant 5)**

Characteristic for the intermediate reheat variant is a very high electric power output. It is an interesting solution without monolithic SiC concrete super-heater protection necessity. Prove has to be provided for the lifetime of cladded platen-type super-heaters. In case of evidence for sufficient long lifetime only the investment costs for cladded heating surfaces and the intermediate reheat compared to the base solution balance against a higher income in electric power sales. Availability and uninterrupted operation time we expect not to variate from the base solution.

**Combination of variants**

The combination of the variants presented is leading to higher efficiencies than the single variant. On the other hand drawbacks need to be accepted for each advantage of individual variants and their multiple combinations. General tendencies were shown starting from a base solution – with fixed parameters – for the purpose of comparison only to show the impact of the different variants. Higher boiler feed water temperatures and lower steam outlet pressures can increase the gross power production up to 30%. Assessment of all advantages and disadvantages for each individual case is necessary to find an optimum solution.

4. Feedback according to challenges and developments of plants with different parameters and boiler concepts

To evaluate the feedback and experience of the plants with different parameters and many years of operation, the plants can be categorized as follows:
Operating Experience with Plants with High Steam Parameters

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter °C</th>
<th>Boiler type</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt; 400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>&gt; 400 &lt; 450</td>
<td>horizontal</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>&gt; 400 &lt; 450</td>
<td>vertical</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>&gt; 450</td>
<td>horizontal</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>&gt; 450</td>
<td>vertical</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>reheating of steam</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>external superheating</td>
</tr>
</tbody>
</table>

Table 14: Categories of boilers related to parameters and concept

Depending on these categories, the feedback according to challenges, modifications, exchange rates and costs from a plant survey is summarized in the chapters below.

4.1. Plants with live steam temperature below 400 °C

Plants with parameter in this category are mainly characterized by modifications like:

- Modification of refractory in the first pass by changing/reducing of refractory system and adding cladding to the upper area in the first pass and second pass, sometimes driven by higher heating values.
- Increasing efficiency by adding economizer heating surface to lower flue gas outlet temperature and increase efficiency.
- Increasing boiler load, often in combination with lowering temperature in radiation part by reducing installation height of the refractory and installing cleaning systems.
- Final super-heater replaced by cladded type to increase life time, caused by the reason of high flue gas temperature and high chlorine content.

4.2. Plants with live steam temperature of 400 °C

Plants with parameter in this category are mainly characterized by modifications like:

- Adding cladding to the upper area in the first pass and second pass to reduce corrosion ratio.
- Increasing efficiency and load by adding evaporator and economizer heating surface.
- Only single tubes of super-heater 2 and 3 are changed.
- Additional protection of connection pipes with shields.

4.3. Plants with live steam temperature between 400 °C and 450 °C

4.3.1. Horizontal boiler type

Plants with parameter in this category are mainly characterized by modifications like:

- Complete change of final super-heater after expected life time.
- Only single tubes of super-heater 2 are changed.
4.3.2. Vertical boiler type
Plants with parameter in this category are mainly characterized by modifications like:

- Increase pitch of the first bundle in the 3rd pass with wider pitch, to reduce pressure loss by fouling.
- Decreased steam parameters to reduce corrosion risk.
- The need of position of the final super-heater in a high flue gas temperature area caused by heat transfer reasons is still a challenge

4.4. Plants with parameter above 450 °C

4.4.1. Horizontal boiler type
Plants with parameter in this category are mainly characterized by modifications like:

- Adding cladding in the second pass to reduce corrosion ratio.
- Exchange of unprotected evaporator walls.
- With restrictions in part load behaviour and at beginning of campaign, the final super-heater can be located in a low corrosion risk area.

4.4.2. Vertical boiler type
Plants with parameter in this category are mainly characterized by modifications like:

- Modification of refractory in the combustion chamber, due to corrosion in cladded area above the grate due to fuel content and high evaporator temperature.
- Adding cladding to the upper area in the 1st pass and ceiling 2nd pass to avoid high temperature chlorine corrosion.
- Modification of protection with refractory of the radiation super-heater 2 in the 2nd pass and later exchange by a cladded type and modification of super-heater arrangement.
- The need of position of the final super-heater in a high flue gas temperature area caused by heat transfer reasons is still a challenge

4.5. Plant with reheating of steam
Plants with parameter in this category are mainly characterized by modifications like:

- Corrosion on Inconel 625 in combustion chamber in main combustion area, by high temperature chlorine corrosion; wall surface temperature of about 320 °C at 95 bar and flue gas temperature > 1,100 °C. Modification of protecting system in combustion chamber by additional ceramic tiles in this area.
- Corrosion on 1st row at inlet to 2nd pass, by limited corrosion and erosion resistance of Inconel 625. Tube shields on first row; lowering steam temperature in the meantime and equalizing temperature profile reduce corrosion ratio.
- Increasing pitch of evaporator grid 3rd pass to lower fouling behaviour.
- Change of pipe material in first bundle of 3rd part to increase life time.
4.6. Plant with external super-heater

Plants with parameter in this category are mainly characterized by modifications like:

- Slagging on tiles up to end of refractory by relative low melting point of fly ash due to RDF quality. In post-combustion zone ashes are only fusible from time to time. Modification of cleaning frequencies of air ventilated tiles by means of shower cleaning system.

5. Evaluation of heat surface life time and maintenance costs

A second goal of the survey was to evaluate the exchange rate of the different heating surface types, the life time of a bundle before exchange and the costs for maintenance and exchange. Altogether it must be stated, that this evaluation was not as easy as it seems. The above mentioned items are caused by many influences like:

- design parameter related to position in corrosion diagram (more or less also directly related to part load behaviour),
- waste type and composition,
- protection concept (cladded or not),
- boiler type (more easy exchange of bundle parts in horizontal boiler type),
- design wall thickness in relation to min. needed wall thickness,
- maintenance concept,
- combustion control and equalizing temperature distribution,
- type of measurement of wall thickness and preventive monitoring.

Nevertheless, an attempt was started to evaluate the feedback of data like shown in the following figures.

Figure 26: Plants built by Steinmüller Babcock Environment or predecessor companies
Figure 26 shows the relation between live steam pressure and live steam temperature, with a deviation of ± 40 K depending on the turbine and water steam cycle concept. The potential to lose wall thickness during operation is shown in the following figures.

Figure 27: Potential of spare wall thickness in economiser and evaporator pipes

Figure 28: Potential of spare wall thickness in super-heater tubes
The evaluation in Figure 27 shows, that the *spare* wall thickness is not related to the steam pressure and more or less depending on material requirements of the final operator. Economiser bundles have usually a very long life time, so a *spare* wall thickness of 2,5 to 3,5 mm seems to be standard in the design and sufficient.

The spare wall thickness of super-heater is not related to the steam pressure (Figure 28). One reason is that super-heater bundles with corrosion risk are protected by cladding. A *reserve* between 3,0 to 4,5 mm is the average standard.

![Figure 29: Availability and operation time versus live steam temperature](image)

Like mentioned in Chapter 1, the chosen parameter have an influence on outage time and availability. Figure 29 shows the tendency to a lower availability and number of operating hours as higher the parameter, but on the other hand the range of availability could be approximately ± 3 % from average value. Also operating time is in a range ± 300 h. Reasons for this matter could be:

- definition of availability,
- maintenance concept,
- kind of protection or no protection of heating surface, and
- items named above as influence to corrosion risk.
Figure 30: Life time rate of final super-heater

Figure 31: Exchange rate of super-heater surface versus live steam temperature
The trend of lifetime of the final super-heater is depending on the live steam temperature (Figure 30). But nevertheless this matter is mainly influenced by the fact if the super-heater is protected by cladding and as well the position in the corrosion diagram and the influence of erosion. Many plants are just changing parts of the heat surface, so that this evaluation does not show the whole picture of maintenance and exchange work.

A partial exchange of heating surface instead of a complete bundle is a common maintenance work during revision. Especially with a predictive monitoring system, this measure can be planned in advance. The amount of exchanged super-heater or final super-heater is shown in Figure 31 and as well depending on live steam temperature. In tendency exchange rate to the complete super-heater increase from 0.5 % at 370 °C up to 2 % with 460 °C. Related to the final super-heater, the exchange rate is about eight times higher.

In combination with the life time of a super-heater bundle and the partial exchange rate, the complete/total exchange rate/anno is shown in Figure 32 and shows as well a trend to higher exchange rates with higher steam parameter.

![Figure 32: Total exchange rate of super-heater including partial and complete exchange](image)

Final super-heaters are the most critical part like shown in Figure 33. Exchange rates with an average value of 10 to 12 % are more than three times higher than exchange rates of the other super-heater parts, evaporator and economiser.
Figure 33: Specific exchange rate of heating surface type versus live steam parameter

Figure 34: Costs and outage time to repair or exchange heat surface
Related to the fact, that the feedback to this question was very low, it is not easy to evaluate the real costs due to the matter that they are depending on:

- boiler and maintenance concept,
- kind and protection of heating surface,
- work in additional or during revision work,
- size of the boiler

and many other influences.

To create a picture, the cost were related to the load/heat input of the boiler. In tendency a relation between specific cost and steam parameter is given and increase from about 2,000 EUR/MW up to approximately 7,000 EUR/MW depending on the steam parameter.

![Figure 35: Specific maintenance costs per MW heat input and year versus live steam temperature](image)

### 6. Conclusion

The analysis of the matter *corrosion rate* depending on chosen steam parameters shows a wide range of influences and parameters and is not easy to evaluate. Feedback from plants in operation is also depending on the former design, operation mode, maintenance and protection concept. As well waste and process quality have a main influence.
Further developments and improvements can increase availability, lower corrosion risk and lower the costs for maintenance. Plants with advanced technologies for high steam parameters and high electrical power efficiency were optimised where necessary during guarantee period and afterwards to become more reliable.

This improvements could be:

- optimise combustion control,
- equalise temperature profile,
- improvement of waste management and change waste quality,
- lowering flue gas temperature,
- implementation of protection layers (refractory with high thermal conductive or cladding),
- maintenance friendly heating surfaces, and
- adjustment of heat surfaces.

Nevertheless the investment costs and higher efficiency are different from plant to plant and must be taken into account, as well as local subsidies.

To create the optimum of steam parameter the calculation of the NPV (net present value, Chapter 1) is a qualified possibility for a final decision and needs to be updated whenever boundary conditions are changed.

The wide range of exchange rates and costs shows as well that this matter is also depending on the individual plant strategy and possibilities and not only a matter of boiler design and parameter.

To include the maintenance or exchange of heating surfaces during a yearly revision can safe costs and outage time. With losses of 50,000 EUR and more per day this factor has a high influence to the real costs in a holistic consideration.

A positive feedback from boiler concepts with final super-heater in a cold area in horizontal pass (< 600 °C) with restrictions in operation during clean boiler can be pointed out. Boiler concepts with super-heater panels in the second pass and flue gas temperature up to 900 °C upstream heat surfaces leads to higher maintenance costs and challenges especially in the upper part of the head surface related to corrosion and erosion, but with an advantage related to part load steam temperature.

The evaluation shows, that a new definition of heating surface life time and guarantee values is necessary, related to the fact that a deviation between partial exchange rate and complete exchange of a heating surface bundle seems to be reasonable.

Monitoring like described in [3, 19, 22, 24] is a good basis to develop predictive maintenance concepts. As well basis studies of the \textit{as built} conditions of a boiler are also a good \textit{start point} to develop improvements and optimized concept for each individual challenge of a boiler [13].
Related to the exchange rate of the super-heater surface the main basis figure is the distance to the transition zone in the corrosion diagram as an indication for corrosion risk. An individual developed guideline [14] recommends a safety margin to decide if additional surface protection in relation to flue gas conditions is necessary or not.

The trend to higher steam parameter and the needs of the maintenance staff leads to developments in the boiler design. Goal of the Steinmüller Babcock Environment development was modular design of convection heat surface bundles like shown in the following picture.

This development is realised since many years and a big advantage related to maintenance time and costs. This solution gives the possibility to change complete bundles during revision work and repair single parts between two revisions. Also for unplanned changes this concept could be a solution for future.

A lot of challenges and experience were presented. The presented plants can be operated successfully and can be used to learn from individual challenges. The knowledge can be utilized to develop new design and protection concepts and as a basis for improvements in the future.

7. Literature


Operating Experience with Plants with High Steam Parameters

Waste Incineration

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The actual book 2016|2017 carries forward the survey of waste-to-energy plants in the Federal Republic of Germany which started in the 1990’s. With the first publication we have two books which complement each other perfectly. Both books provide extensive information about the installed technology and the environmental impact of the waste-to-energy plants. The quality of the new inquiry has been extended in terms of the technical data. Existing gaps regarding the data were partially filled.

This is the result from the considerable assistance of numerous plant operators. The publication on hand shall be seen as an interim report. The work on the data acquisition will be continued. For this reason we ask plant operators and manufactures to critically review the release data.

- 33 municipal solid waste incineration plant
- 7 solid recovered fuel power plant
- 1 Sonderabfallverbrennungsanlage

The further investigations will be extended to the missing German waste-to-energy plants as well as to plants in other countries.

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