ESP Performance Enhancements by
$\text{SO}_3$ - Conditioning

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- ESP Basics
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  - CFD-Modeling for ESP Optimization
  - The Step Beyond: Coal/Dust Characteristics & Operational Optimization
  - Installation of Five New SO₃ Conditioning Units in STEAG Plants
  - Performance with Low Sulfur Coal

- Summary
Project Background: Installation of Five SO$_3$ – Conditioning Units at Steag

Present Experience at Steag in Herne III since 2004

Decision of 2008 – five new Pentol units:

- Lünen 6 and 7  25 and 45 kg$_S$/h  150 / 350 MW$_{el}$
- Herne IV   80 kg$_S$/h  500 MW$_{el}$ + district heating
- West 1/2   each 45 kg$_S$/h  2 x 350 MW$_{el}$
## History: First SO$_3$ Unit at Herne III

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>Commissioning Unit III</td>
</tr>
</tbody>
</table>
| 1986 | Coal switch to 100% low volatile German Coal, Re-Equipping:  
Ball-Mills, Low NO$_x$-Burners  
Additional ESP (downstream): Dust Emission 150 mg/m$^3$ (Performance test 70-120 mg/m$^3$) |
| 1987 | Commissioning FGD / Tail End SCR |
| 1995 | Coal switch to Imported Coal for the first time |
| 1996 | Extension of ESP Rear Section by 10% |
| 1998 | Installation of a new ESP-Control System (Prevent Back Corona) |
| 2000 | Flow Optimization by CFD-Modeling |
| 2001 | Co-Firing of Animal Meal |
| 2002 | Increased usage of Imported Coal |
| 2003 | Trials to improve dust collection by blending high ($S \approx 3\%$) with low sulfur coal |
| 2003 | Co-Firing of Sewage Sludge (30 000 tpy) |
| 2004 | Installation of SO$_3$-Conditioning |
| 2007 | Optimization of AP-Slip by new sealing |
Challenges in Dust Removal

- Imported hard coal replaces regional coal stepwise
- Co-firing of auxiliary fuel
- Improvement of ESP dust separation due to input of imported coal / low sulfur coal
- Changes in regulations, new emission limits according to 13. BImSchV: Dust emissions from 50 lowered to 20 mg/Nm³
- Difficult to add new ESP/ ESP fields and high invest cost for precipitator field extension
ESP Basics: Resistivity

Resistivity

Velocity

Performance

Legend:

\[ \eta = \frac{R - r}{R} = 1 - e^{-w \cdot \frac{A}{V}} \]

\[ w = \ln \left( \frac{R}{r} \cdot \frac{\dot{V}}{A} \right) \]

\[ A = \ln \left( \frac{R}{r} \cdot \frac{\dot{V}}{w} \right) \]

\begin{itemize}
  \item \( R \): clean gas dust
  \item \( r \): raw gas dust
  \item \( A \): separating surface
  \item \( \dot{V} \): flue gas volume flow
  \item \( \eta \): ESP efficiency
\end{itemize}

Improved by SO\textsubscript{3}-Conditioning
Process Steps

1. Electron emission
   • Corona discharge

2. Charging of dust particle
   • Diffusion charging for particles < 0,5 µm
   • Field charging for particles > 0,5 µm

3. Transport of charged particles
   • Coulomb force
   • Stokes law

4. Dust Agglomeration on collecting electrode
   • Adhesion forces
   • Voltage

5. Dust Removal from Collecting electrode
   • Mechanical rapping
   • Shearing forces
Back Corona Effects

Through back corona ash particles are going back into the flue gas forming small craters in the ash layer.

Extension of dust emission downstream ESP is caused by this effect.

Back corona is avoided by modern ESP control systems.

Source: Rothemühle
Enhanced ESP Performance: Utilized Ways

- Enhanced Process and ESP Control
- Mechanical shape of the filter and rapping interval optimization
- \( \text{SO}_3 \) – Conditioning
- Smoothing velocity and strand avoidance – achieved by CFD optimization
- Reduction of Air Heater Slip
Prior to modifications

**Ductwork and guiding arrangements**

Guide vane level in duct section between air heater and ESP

Gas distributing wall made of "X-Richtblech" flow-directing plates

Perforated guide vanes and dividing wall for distribution to two ESP trains
- FLUENT model of the present ESP
CFD Modelling for ESP Optimization

Computational model

- FLUENT model variations

- Pressure drop at ESP outlet
- Edge areas of gas distributing walls
- Gas distributing walls made of "X-Richtblech"
- Inflow grate
- Guide vanes with extensions arranged on various levels
- Different hopper partitioning wall arrangement options
CFD Modelling for ESP Optimization

Velocity pattern

- Prior to modification

velocities in m/s
CFD Modelling for ESP Optimization

Velocity pattern

- **Optimized case**
  velocities in m/s
Velocity pattern

- Optimized Case Detail: Sloping plates in first hopper
velocities in m/s
CFD Modelling for ESP Optimisation

Modifications

- **Hopper interior**
  - grate of sloping plates in the first hopper row
  - standard partitioning wall in the second hopper row

- **Extension of guide vanes and inlet flow grate**
  - extension of two guide vanes

- **Gas distributing walls**
  - partial replacement of plates to implement the determined pressure drop coefficients

- **Outlet pressure drop**
  - Installation of an outlet wall with vertically staggered pressure drop coefficients
## Fuel Qualities

### Coal Analysis

<table>
<thead>
<tr>
<th>Coal Analysis</th>
<th>GER Walsum</th>
<th>GER Niederb.</th>
<th>NOR Svalbard</th>
<th>COL Cerrejon</th>
<th>ZA Kleinkopje</th>
<th>Sewage Sludge</th>
<th>Animal Meal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (raw) %</td>
<td>10.7</td>
<td>12.1</td>
<td>6.8</td>
<td>11.9</td>
<td>7.2</td>
<td>6.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Ash (raw) %</td>
<td>21.3</td>
<td>22.0</td>
<td>27.1</td>
<td>7.7</td>
<td>29.1</td>
<td>36.0</td>
<td>26.4</td>
</tr>
<tr>
<td>Volatile (waf) %</td>
<td>32.8</td>
<td>12.9</td>
<td>43.7</td>
<td>40.2</td>
<td>29.1</td>
<td>88.0</td>
<td>89.2</td>
</tr>
<tr>
<td>LCV MJ/kg</td>
<td>22.59</td>
<td>22.72</td>
<td>22.66</td>
<td>25.52</td>
<td>25.00</td>
<td>11.96</td>
<td>16.61</td>
</tr>
<tr>
<td>Sulfur (raw) %</td>
<td>0.82</td>
<td>0.73</td>
<td>3.95</td>
<td>0.57</td>
<td>0.45</td>
<td>1.77</td>
<td>0.49</td>
</tr>
</tbody>
</table>

### Ash Analysis, all in %

<table>
<thead>
<tr>
<th>Ash Analysis</th>
<th>GER Walsum</th>
<th>GER Niederb.</th>
<th>NOR Svalbard</th>
<th>COL Cerrejon</th>
<th>ZA Kleinkopje</th>
<th>Sewage Sludge</th>
<th>Animal Meal</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>50.5</td>
<td>54.8</td>
<td>54.0</td>
<td>60.9</td>
<td>49.7</td>
<td>19.9</td>
<td>4.3</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>23.7</td>
<td>24.6</td>
<td>19.4</td>
<td>19.9</td>
<td>27.0</td>
<td>8.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>9.4</td>
<td>8.4</td>
<td>12.5</td>
<td>8.2</td>
<td>6.8</td>
<td>17.8</td>
<td>0.6</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.93</td>
<td>0.94</td>
<td>0.98</td>
<td>0.94</td>
<td>1.84</td>
<td>0.63</td>
<td>0.04</td>
</tr>
<tr>
<td>CaO</td>
<td>4.04</td>
<td>2.30</td>
<td>3.72</td>
<td>2.79</td>
<td>7.56</td>
<td>18.20</td>
<td>44.70</td>
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<tr>
<td>MgO</td>
<td>2.48</td>
<td>2.39</td>
<td>1.57</td>
<td>2.00</td>
<td>1.64</td>
<td>2.60</td>
<td>1.32</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.95</td>
<td>0.82</td>
<td>1.22</td>
<td>0.79</td>
<td>0.01</td>
<td>0.94</td>
<td>4.77</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.59</td>
<td>4.27</td>
<td>2.30</td>
<td>1.73</td>
<td>0.48</td>
<td>1.31</td>
<td>1.33</td>
</tr>
<tr>
<td>SO₃</td>
<td>3.71</td>
<td>3.28</td>
<td>3.41</td>
<td>1.76</td>
<td>2.59</td>
<td>2.41</td>
<td>0.84</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.62</td>
<td>0.42</td>
<td>0.73</td>
<td>0.25</td>
<td>1.53</td>
<td><strong>25.70</strong></td>
<td><strong>36.30</strong></td>
</tr>
</tbody>
</table>
Background: Resistivity - Coal & Ash Properties

- **Charge Carriers** improve performance
  - Charge Carrier: water
  - Hygroscopic: sulfur trioxide (from SO₃ conversion)
  - Charge Carrier: soda (Na₂O), potassium oxide (K₂O)
  - Iron(III) oxide (Fe₂O₃): catalytic action to convert SO₂ to SO₃
  - low resistivity → high particle migration velocity

- **Neutral Particles** reduce performance
  - Natural insulators: silica (SiO₂), alumina (Al₂O₃)
  - Tend to neutralize SO₃: lime (CaO), magnesia (MgO)
  - high resistivity → low particle migration velocity
“shapen the resistivity curve and flatten the dust curve with SO₃”

w/o SO₃-Conditioning

Plant Load

Opacity

w/ SO₃-Conditioning

Plant Load

Opacity

“Coal Spots”

Hard Coal Cerrejón, Columbia

1 ppm SO₃ = 3.57 mg/Nm³
The SO$_3$ plant consists of a liquid sulfur tank and a process container.

Liquid sulfur is oxidized with pre-heated air and converted into SO$_3$ by means of a catalyst.

A set of injector probes installed in the flue gas duct distribute the SO$_3$/air mixture evenly to the flue gas before the ESP.

SO$_3$ condenses completely on the fly ash.

Electrical resistivity of particles is lowered.

ESP can work on its design point.

Typical injection rate: 10 – 80 mg/Nm$^3$ SO$_3$. 
SO$_3$ - Conditioning Plant Layout

Air

Compressed Air
(dry)

Liquid Sulfur (140 °C)

Blower

Air Heater

400 °C

SO$_3$

Sulfur Burner
(self-ignition at 250 °C)

Catalyzer
(450 °C)

Flue Gas
Injection Nozzle Pipes

SO$_2$

H$_2$SO$_4$

H$_2$O

Condensate

Liquid Sulfur Pipe

140 °C

400 °C

Liquid Sulfur Tank (140 °C)

IP-Steam
(secured)

3.5 bar

IP-Steam

Flue Gas
110 - 140 °C
SO\textsubscript{3} Compact Unit in Container

- Air Heaters
- Air Blower with filter box
- Catalyzer
- Sulfur Burner
- Unit Control Cubicle
- Sulfur Tank Control Cubicle
Liquid Sulfur Storage Tank

- Breather
- Level Meter
- Sulfur Pumps
- Sulfur Dosing Valves
Configuration of SO$_3$ Injection Pipes

*former design*

*improved lightweight design*
Black Box S7 of Evonik's first unit at HKW Herne III

Now: DCS embedded, e.g. ABB Procontrol P14 Lünen 7
Load – Coal/Sulfur Dosing Diagramm for HKW Herne III

- e.g. German high sulfur coal
- e.g. South African high ash and low S
- e.g. import blend
Investigation of possible risks

- SO$_3$ in flue gas after ESP → e.g. Lünen: 4,3 mg/Nm$^3$ (2 to 7 mg, ESP tilt)
  e.g. Herne: 9,0 mg/Nm$^3$ (8 to 11)

- Aerosol at stack → no, SO$_3$ at detection limit below 2 mg/m$^3$

- fly-ash transport → no issues, fluidization flutes working well

- fly-ash properties → pH slightly lowered, SO$_3$ slightly increased

- Corrosion → no impact since 2004
Gypsum Quality increase for HKW Herne III

<table>
<thead>
<tr>
<th>Operation w/o SO₃-Unit</th>
<th>Operation w/ SO₃-Unit</th>
<th>fuel change</th>
<th>11 pm – 8 am Block III outage</th>
</tr>
</thead>
</table>

- Operation w/o SO₃-Unit
- Operation w/ SO₃-Unit

- Product Limit
- Daily Average: Dust at Stack / mg/Nm³

June 2021
- 20
- 21
- 22
- 23
- 24
- 25
- 26
- 27
- 28
- 29
- 30

July 2021
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15

Gypsum Whiteness / %
- 60
- 70
- 80

- 15
- 10
- 5
- 0
Six Units at Evonik Steag

Evonik’s 1st SO2-Unit Herne III was taken into operation in 2004
Six Units at Evonik Steag

Lünen 7

..inside

Lünen 6..
## Acceptance Test Run Herne IV

<table>
<thead>
<tr>
<th>Cogeneration Power Plant Herne Unit IV</th>
<th>500 MW Dry Bottom Furnace</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without SO3 Conditioning</td>
</tr>
<tr>
<td>Case</td>
<td>Design</td>
</tr>
<tr>
<td>Fuel</td>
<td></td>
</tr>
<tr>
<td>Lower Calorific Value (MJ/kg)</td>
<td>Ruhr</td>
</tr>
<tr>
<td>Ash (raw) mass.%</td>
<td>30</td>
</tr>
<tr>
<td>Moisture (raw) mass.%</td>
<td>10</td>
</tr>
<tr>
<td>Volatiles (waf) mass.%</td>
<td>30</td>
</tr>
<tr>
<td>Sulfur (raw) mass.%</td>
<td>1,2</td>
</tr>
<tr>
<td>Ash CaO mass.%</td>
<td>--</td>
</tr>
<tr>
<td>Na2O mass.%</td>
<td>--</td>
</tr>
<tr>
<td>Fe2O3 mass.%</td>
<td>--</td>
</tr>
<tr>
<td>Primary Inclusion mass.%</td>
<td>--</td>
</tr>
<tr>
<td>Conditioning</td>
<td></td>
</tr>
<tr>
<td>Sulfur- Dosing (kg/h)</td>
<td>0</td>
</tr>
<tr>
<td>Sulfur- Dosing (max.) ppm</td>
<td>--</td>
</tr>
<tr>
<td>SO3 Concentration Flue Gas ppm</td>
<td>--</td>
</tr>
<tr>
<td>ESP Operation Figures</td>
<td></td>
</tr>
<tr>
<td>Dust Concentration after Boiler mg/Nm³</td>
<td>50,000</td>
</tr>
<tr>
<td>Dust Concentration before FGD mg/Nm³</td>
<td>50</td>
</tr>
<tr>
<td>Dust Concentration before FGD 3 fields off mg/Nm³</td>
<td>-</td>
</tr>
<tr>
<td>Migration Velocity cm/s</td>
<td>7,49</td>
</tr>
<tr>
<td>ESP-Configuration</td>
<td></td>
</tr>
<tr>
<td>Space of Lanes mm</td>
<td>400</td>
</tr>
<tr>
<td>Internal Power Consumption KW</td>
<td>--</td>
</tr>
<tr>
<td>Total Internal Power Consumption KW</td>
<td>--</td>
</tr>
<tr>
<td>Spec. Power Demand KW/m³/s</td>
<td>--</td>
</tr>
<tr>
<td>Spec. Retention Surface m²/m³/s</td>
<td>99</td>
</tr>
</tbody>
</table>
Summary

- Great flexibility for coal quality
- No load restrictions by Dust Emission Limit
- Decrease of wear and tear at the ID fans
- Dust input to FGD very low:
  - Whiteness of gypsum > 85% possible, also better crystal growth expected
  - Keeping the Emission-Limit of 20 mg/Nm³ w/o expensive ESP-extension
  - Installation of the SO₃-Conditioning Plant during operation. Only short outage necessary for assembly of the injection tube and nozzles
- Investment costs relatively low (~ 4 €/kW = ~2.9 $/kW)
- Operation and maintenance costs relatively low (Sulfur ~70 €/t = ~55 $/t)
- SO₃-Conditioning Plant fully integrated into the DCS
To find out why the ESP did not collect the dust at its design level, dust resistivity measurements have been conducted.

- The resistivity probe is placed in the flue gas duct
- An integral cleaning system allows repeated tests in a single location without removing the probe from the dust duct
- 4” Test Port Opening required

- Dust resistivity in raw gas
  w ~ resistivity [cm/s] up to $3 \times 10^{13} \Omega \text{cm}$ was measured