Meeting Increasingly Stringent Emissions Regulations for Coal Fired Power Plants

- Emissions limits for Coal Fired Power Plants – status and trends
- Boiler and emission controls technologies – current state-of-the-art
- Focus on combustion technology for coal and biomass conversions
New Build Coal Fired Power Plant Trends

Power Plant Orders > 250MW

World gross electricity production, by source, 2016

1328 GW OF NEW PLANT ORDERED SINCE 2000

NEARLY 40% FROM COAL

119GW OF NEW PLANT ORDERED 2015-16, BUT DECLINING

New Build Coal Fired Power Plant Trends
Reducing Stack Emissions Limits

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>IED / European Standard</th>
<th>World Bank (WB) IFC (1)</th>
<th>CHINA GB 13223-2011</th>
<th>TURKEY</th>
<th>INDONESIA</th>
<th>INDIA(4)</th>
<th>SOUTH KOREA(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>150 mg/Nm³</td>
<td>200 mg/Nm³</td>
<td>100 mg/Nm³</td>
<td>200 mg/Nm³</td>
<td>750 mg/Nm³</td>
<td>(300 mg/Nm³)</td>
<td>164 mg/Nm³ (60 ppm)</td>
</tr>
<tr>
<td>SO₂</td>
<td>150 mg/Nm³</td>
<td>200 mg/Nm³</td>
<td>100 mg/Nm³</td>
<td>200 mg/Nm³</td>
<td>750 mg/Nm³</td>
<td>(200 mg/Nm³)</td>
<td>220.8 mg/Nm³ (80 ppm)</td>
</tr>
<tr>
<td>PM</td>
<td>10 mg/Nm³</td>
<td>30 mg/Nm³</td>
<td>30 mg/Nm³</td>
<td>30 mg/Nm³</td>
<td>100 mg/Nm³</td>
<td>(60 mg/Nm³)</td>
<td>20 mg/Nm³</td>
</tr>
<tr>
<td>HG</td>
<td>Not defined / 0.03 mg/Nm³</td>
<td>Not defined</td>
<td>0.03 mg/Nm³</td>
<td>Not defined</td>
<td>Not defined</td>
<td>0.03 mg/Nm³</td>
<td>Not defined</td>
</tr>
</tbody>
</table>

1. Emission guidelines from World Bank IFC, 2009 Environmental, Health, and Safety Guidelines. (for DA areas (DA = Degraded Airshed = poor air quality)).
2. Generation capacity > 500 MWe, from 1st Jan 2005 to 2016
4. Bold values for new plant after Jan 01 2017 Plant > 500 MWe
5. From German Regulation / 13. BimSchV,
6. Increased to 200 in certain provinces.
7. From 2015
8. Reduced to 20 for certain regions.
9. Reduced to 50 for certain regions.
10. mg/Nm³ = milligrams per normal cubic meter at 7% O₂, 25°C and 1.013 bar.
New Build Coal Fired Power Plant Trends
Reducing Stack Emissions Limits

Future Ultra-Low Emission Limits

- Drive to even lower emission limits for NOx, SOx and PM – eg new South Korean limits:
  - PM – 5 mg/Nm³
  - SO₂ – 25ppm (71.5 mg/Nm³)
  - NO₂ – 15ppm (30.8 mg/Nm³)

PM₂.₅
- In most countries particulate matter from coal fired power plant is not distinguished by size at the stack, but may be distinguished in ambient air.
- PM₂.₅ concern because of possibility for deep penetration to lungs.
- PM₂.₅ classified as primary and secondary:
  - Primary is filterable fine particulate matter (eg fly-ash)
  - Secondary is formed by reactions of other pollutants (eg SOx, NOx, NH₃)

Doosan State-of-the-Art Technologies
for Boilers and Emission Controls
Ultra-Supercritical Boiler Technologies for High Efficiency

- Highest efficiency achieved via steam cycle optimisation by a combination of:
  - USC steam parameters at turbine inlet
  - Regenerative feedwater heating to increase boiler feed water temperature
  - Condenser pressure / LP Turbine last stage blade optimisation
- Emission reduction resulting from higher efficiency is substantial:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Supercritical</th>
<th>Ultra-Supercritical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Steam Pressure / Temperature</td>
<td>245 bar / 565°C</td>
<td>280 bar* / 600°C</td>
</tr>
<tr>
<td>Reheat Steam Pressure / Temperature</td>
<td>40 bar / 565°C</td>
<td>60 bar** / 610°C</td>
</tr>
<tr>
<td>Net Plant Efficiency (% LHV)</td>
<td>41.9</td>
<td>44.0</td>
</tr>
<tr>
<td>Emissions (CO₂, SO₂, NOₓ, PM)</td>
<td>Base</td>
<td>-5%</td>
</tr>
</tbody>
</table>

*280 bar ≈ 4060 psi
**60 bar ≈ 870 psi

What happens when we use higher temperature and pressure?

- When water is above 221 bar and 374°C we no longer have any phase change between water and steam – we just have a continuous change in density as the fluid is heated
- Because there is no phase change we can no longer use a traditional 'natural circulation' type boiler and we instead use a 'once-through' boiler

'SPIRAL' FURNACE
Ultra-Supercritical Boiler Technologies for High Efficiency

- **GHECO-ONE, THAILAND**
  - 1 x 700MW
  - SH 569℃/ RH 569℃ 255 atg
  - Sub-bituminous Coal

- **AIN SOKHNA, EGYPT**
  - 2 x 650MW
  - SH 540℃/ RH 540℃ 265 atg
  - Mazout Oil

- **YEONG HEUNG 5.6, S. KOREA**
  - 2 x 870MW
  - SH 569℃/ RH 569℃ 251 atg
  - Sub-Bituminous and Bituminous Coals

- **SHINBORYEONG, S. KOREA**
  - 2 x 1000MW
  - SH 613℃/ RH 624℃ 274 atg
  - Sub-Bituminous and Bituminous Coals

**EVOlution IN STEAM CONDITIONS**

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**First 1000 MW USC Boiler in Korea**

<table>
<thead>
<tr>
<th>Name of Plant</th>
<th>Shinboryeong #1,2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>1,000MW x 2</td>
</tr>
<tr>
<td>Country</td>
<td>KOREA</td>
</tr>
<tr>
<td>Customer</td>
<td>KOMIPO</td>
</tr>
<tr>
<td>Contract Award</td>
<td>Nov. 2011</td>
</tr>
<tr>
<td>COD</td>
<td>Jun. 2017 (Under Commissioning)</td>
</tr>
<tr>
<td>Fuel</td>
<td>Sub-bituminous Coal</td>
</tr>
<tr>
<td>HHV</td>
<td>5,600 kcal/kg</td>
</tr>
<tr>
<td>Moisture</td>
<td>17%</td>
</tr>
<tr>
<td>Ash</td>
<td>7.8%</td>
</tr>
<tr>
<td>Type of boiler</td>
<td>PC Boiler (Opposed firing)</td>
</tr>
<tr>
<td>Steam Condition</td>
<td>SH 613℃/ RH 624℃, 274 atg</td>
</tr>
<tr>
<td>Emissions (Stack)</td>
<td>NOx: 35ppm, SOx: 50ppm, PM: 15mg/Nm³</td>
</tr>
</tbody>
</table>

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Unit #1 (21st Mar. 2017)

Unit #2 (21st Mar. 2017)
Ultra-Supercritical Boiler Technologies for High Efficiency

Boiler Features – 1000 MW Design

- Proven Two pass arrangement (Pendent and Horizontal)
- Stable RH steam temperature control for wide range coals with flue gas bias damper – higher efficiency at lower load
- High performance Low NOx burner
- And OFA
- Once-Through boiler technology with proven lower spiral wall tube and upper vertical wall tube
- Vertical mills with dynamic classifiers
- Proven capability for rapid starting with two shift operation
  - 2 Axial FD fans
  - 2 Axial ID fans
  - 2 Axial PA fans
  - 2 Trisector AHs

Materials for USC Conditions

- Current USC steam parameters require a spectrum of ferritic and austenitic alloy steels for highest temperature components.
- Material selection mainly depends on 1) strength as a function of tensile and creep properties and 2) resistance to steam side oxidation.
  - Careful design of flow distribution can reduce operating conditions 3)
- Tube Temp. (Outlet Header Side)
State-of-the-Art Emissions Controls Technologies

Typical Arrangement on Modern Plant

- **Primary NOx Control**: Low-NOx Combustion System
- **Secondary NOx control**: SCR
- **Flue Gas Desulphurisation and Gas-Gas Heater**
- **Electro-static Precipitator or Bag Filter**

State-of-the-Art Emissions Controls Technologies

**Primary NOx Control**

- **TYPICAL COAL RANGE FOR NEW ASIAN PROJECT**
- **TYPICAL ORIGINAL DESIGN RANGE FOR UK PLANT**

- Project fuel ranges become ever wider to ensure flexibility to accommodate changes in international coal sourcing.
- Mature low NOx combustion systems deliver primary NOx reduction
  - Current performance expectation circa 200 to 300 mg/Nm³ NOx with <3% Carbon in Ash
State-of-the-Art Emissions Controls Technologies

**SCR for NOx Control**
- Capable of up to 80-90% NOx reduction

- **Case Study:** Ratcliffe, United Kingdom
  - 4 x 500 Mwe Units

- **Case Study:** Castle Peak B, Hong Kong
  - BOFA System for Primary NOx control
  - Compact “In-Duct” SCR Arrangement

**Flue Gas Desulphurisation**

**Wet Lime / Limestone FGD**
- 205 absorbers installed (110 absorbers in China)
- 71 GW, total capacity
- Maximum absorber size: 1,000 MWₑ

- **Case Study:** Rugeley, United Kingdom
  - WLFGD retrofit
  - Plant output: 2 x 500 MW

**Seawater FGD**
- 14 absorbers installed
- 8 GWₑ total capacity
- Maximum absorber size: 700 MWₑ

**Circoclean® FGD / FGC**
- 90 reactors installed (18 reactors in China, 26 in the USA)
- 13 GWₑ total capacity
- Maximum reactor size: 305 MWₑ
Combustion Technology for Coal

Fuel Rank (ASTM)
Combustion System

Low NOx Combustion
- Control the availability of Oxygen to the combustion process
- Reduce peak temperatures in combustion zone
- Fuel NOx preferentially goes to N2
- Carbon in ash and CO increase!

Low NOx Burner
- Ignition and flame stability
- High rate of de-volatilisation to get Nitrogen out of fuel quickly
- Segregate air from fuel to control the rate of NOx formation

Combustion System Development Approach

Development Timescale 18-24 Months
Combustion System Development Approach

- ½ or ¾ Geometric scaled models
- Pumice to represent pulverised coal
- Characterise outlet distribution and pressure drop
- Indication of fuel drop-out and erosive wear
- Validation of CFD models

Combustion System Development Approach

CFD Modelling - Component Design and Combustion System

- Optimise PA, flameholder, deflector, swirler designs
- Confirm robust design
- Fuel supply
- Fuel type
- B2S (A)
- Flow split
- Swirl
- Furnace

Fuel Concentration at Load and Turndown
Swirler Vane Optimisation and Velocity Distribution
Flameholder Optimisation and NO Rate
Min Swirl Design Max Swirl Fuel Change

Furnace Temperature and NO Profiles
Combustion System Development Approach

Combustion Test Facilities

- Isothermal aerodynamic characterization (swirl number and k factor)
- Parametric testing of burner settings, design / off design operation (PA:PF, stoichiometry excess air, residence time, turndown)
- In-flame gas and solids sampling / flame mapping – CFD validation

Combustion System Development Approach

Advanced D NOx Burner

Description:
- Deep stage (<110 ppm, 5% U/L)
- Developed 2016-17
- Simulation-led (2 concepts)

Key Features:
- Swirled air
- Toothed flameholder
- TA deflector
- High swirl
- Low RDL (1 kPa)

Key Results:
- CFD comparable to test
- 33% improvement on D-NOx for similar UBL
- Turndown to 33% (3:1)
How Does a Switch to Biomass Control Emissions?

- **Conventional Pollutants**
  - Biomass has lower levels of pollutant causing elements such as sulphur and nitrogen
  - Biomass burns with a cooler flame reducing NOx

- **Carbon Dioxide**
  - Biomass is renewable
  - Biomass can lead to net carbon removal from the atmosphere in combination with CCS
How Does a Switch to Biomass Control Emissions?

<table>
<thead>
<tr>
<th>Cleaner fuels = lower emissions</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Coal use 1990</th>
<th>Sulphur % ar</th>
<th>Nitrogen % ar</th>
<th>Ash % ar</th>
<th>Chlorine % ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>1.4</td>
<td>15</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coal use 1990</th>
<th>SO$_2$ mg/Nm$^3$</th>
<th>NOx mg/Nm$^3$</th>
<th>Dust mg/Nm$^3$</th>
<th>HCl mg/Nm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3750</td>
<td>650</td>
<td>50</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

Typical values for UK market
ar is "as received"
All emissions at standard 6% O$_2$ dry conditions

Lynemouth Power Station: a Good Candidate for Biomass

<table>
<thead>
<tr>
<th>Closure at the end of 2015 due to lack of SOx and NOx controls to meet IED TNP limits</th>
<th>Biomass conversion offered a way to meet emissions limits because biomass is cleaner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power station was becoming uneconomic due to rising price of carbon</td>
<td>Biomass conversion offered a way to avoid the carbon floor price because the fuel is renewable</td>
</tr>
<tr>
<td>Biomass is an expensive fuel and efficiency is important</td>
<td>North Sea cooling, upgraded turbines &amp; condensers, despite moderate size and steam conditions probably UK’s most efficient coal station</td>
</tr>
<tr>
<td>Benefit of a CfD from the UK government of £105/MWh, ratified by EC, for 10 year period</td>
<td>Drive to maximise availability, efficiency and power output and extend life</td>
</tr>
<tr>
<td>3x140 MWe size made logistics manageable</td>
<td>Helped gain EC approval</td>
</tr>
<tr>
<td>Power station can reuse most of the systems and components which have good residual life</td>
<td>Reducing capital cost for green electricity</td>
</tr>
</tbody>
</table>

CID Contract for Difference
EC European Commission
Lynemouth: Comprehensive Conversion

40% unit efficiency to be maintained
140MWe power output to be retained
IED minimised emissions

Maximum safety
10 year life

- New fuel feeding system
- Mill modifications and new dynamic classifiers
- Replacement PF piping
- Heat balance correction by PA cooler
- New low NOx bespoke biomass burners
- New BOFA system for further NOx control
- Upgraded oil system
- Furnace and heating surface cleaning extension
- No heating surface changes
- 36 new fans across the 3 units
- New dry bottom ash system
- ESP upgrade
- New fly ash system

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BOFA  Boosted over-fire air
PA  Primary air
ESP  Electrostatic precipitator

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BIOMASS COMBUSTION SYSTEM

Biomass Burner Development and Application - Challenge

- Properties of wood pellets and biomass in general differ significantly from coal – greatest challenge is the difference in milling characteristics and resultant particle size which presents a challenge to ignition point and stability.
- Integrated combustion system solution:
  - Mill modification with dynamic classifier to provide adequate fineness and reduced size to aid early ignition and combustion efficiency.
  - Replacement PF pipework and fans to ensure no fuel dropout and optimum distribution by installing the VARB trifurcator.
  - Replacement burners and reduced burner zone stoichiometry to ensure 180 mg/Nm³ NOx capability
  - Boosted Over-Fire Air to control burnout and CO production at acceptable levels.

Typical coal particle sizing:
70-80% < 75 microns
99% < 300 microns

Wood pellets
30-55% < 500 microns
95 – 98% < 2000 microns

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BIOMASS COMBUSTION SYSTEM

Low-NOx biomass burner Design and Features

Regulating Total Air Control Damper to control burner-burner air distribution
Secondary Air Damper to control internal flame staging – optimised during commissioning
Secondary and tertiary swirlers for flame structure control – optimised during commissioning
Fuel Collectors to distribute fuel at PA exit
Flame Holder
Large PA annulus for ignition stability

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BIOMASS COMBUSTION SYSTEM

Boosted Over Fire Air

- Boosted OFA achieves generous staged residence time for NOx control whilst also giving sufficient burn-out residence time to control combustion efficiency.
- Anticipated NCV loss 0.5% and CO < 250 mg/Nm³

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BIOMASS COMBUSTION SYSTEM

Fuel Delivery

- New Dynamic Classifier
- Target Fineness: 55% < 0.5 mm
  98% < 2 mm
- Extended Fuel Inlet Pipe
- New Cone to distribute fuel
- Block centre hole of roller to eliminate hold-up
- Higher velocity throat
- Retained Original scheme of 3 lines per min with trifurcators
- Increased transport velocity to avoid PF drop out

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Conclusions

- Energy demand growth in Asia, India and some other regions continues to drive investment in new coal-fired power plants.

- Ultra-Supercritical Technology with steam temperature > 600°C is now state-of-the-art with unit sizes between 350MW and 1000MW – project developers and financiers are implementing this technology with consequent increase in efficiency and reduction in emissions for new coal-fired fleet.

- Emissions legislation is rightly becoming increasingly stringent, both in emission limits and in scope albeit with some regional anomalies.

- State-of-the-art emissions control technologies can meet the requirements of the current legislation, project developers and financiers. However, the time is never more urgent for R&D efforts for ever greater emissions reduction.

- Biomass conversion offers an effective route to life extend exiting coal-fired assets with significantly lower emissions.
Thank you

Questions?

BIOMASS COMBUSTION SYSTEM
Biomass Burner Development and Application

TILBURY
Single Stage
Modified MK III Burner
- Reduced CA tube size to reduce PA velocity via PA annulus area increase

IRONBRIDGE
Single Stage
Modified Robtis Burner
- Reduced CA tube size 9 to 6 in to reduce PA annular velocity to 20 m/s via PA annulus area increase
- Modifications to fuel delivery (removal of collectors, straighteners and lifter bars) to generate stable ignition

DRAX
Two Stage
Modified MK III Burner
- Reduced PA velocity
- Single air register

CCTF
Low NOx Two Stage
Verification of optimised MK III burner for two-stage Biomass firing:
- Large PA annulus
- Dual register design
- 45-50% NOx reduction

Yeong Dong 1
Low NOx Two Stage
Conversion of 125MW plant with downshot fired boiler

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