Coal Fired Power Stations Operating at Higher Temperatures

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Venue: John Dalton Building, Manchester Metropolitan University

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Objectives of the presentation

- Boiler - Introduction
- Coal fired boilers
- Application of Rankine cycle in power station
- Benefits of high temperature & pressures
- Efficiency
- Boiler arrangement
- Boiler components - Typical furnace, superheater, reheater and economisers
- Supercritical and Ultra supercritical boilers
- References Super critical and ultra supercritical plants designs
- Material selection
- Emissions - Environmental Abatement Technologies
- Regulations
Boiler primary function -
Evaporation of water to steam (at high pressure)
Boiler Classification

Fuel:
- coal
- Oil
- Gas

Steam pressure:
- Sub critical
- Super-critical
- Ultra Super-critical

Firing arrangement:
- Front/ Rear wall
- Tangential firing
Boiler Classification contd.

**Supporting Structure**
- Top supported
- Bottom supported

**Draught system**
- Natural draught
  - Forced
  - Induced
  - Balanced
- Mechanical Draught

**Flue gas flow path**
- Single pass
- Multiple pass
Effects of Superheat and reheat

Temperature

Entropy

Critical point
Saturation line
Liquid region
Mixed (Liquid and Vapour) region
Vapour (steam) region

1
2
3
4
5
Steam pressure and enthalpy relationship
Boiler

Power generation boilers generate high pressure steam to be sent for turbine rotation.
Super Critical means no distinction between water and steam

* Thermodynamic quantity

** Parsons Brinckerhoff**
Natural Circulation

- Used for the systems operating below the critical pressure of the steam
- Needs extremely large-diameter furnace wall tubes of high-alloy materials and downcomer systems, risers, and drum internals.
- For drum and water wall circuitry, the max. practical system pressure shall be about 2,800 psig (19.3 MPa gauge)
- This limits the available pressure drop for superheater cooling when the required superheater outlet pressure is above 2,650 psig (18.3 MPa gauge)
Once through boilers

- In once through boilers, a steam separator is installed instead of drum.
- There is no recirculation and therefore it called once through.
- The steam separator performs initially which separates the water from steam.
- Feed water is converted into steam.
- It is much smaller than steam drum and thickness is considerably lower than steam drum.
Examples of various manufacturers designs

CE, USA design

B&W, USA design

Doosan, South Korea

Foster Wheeler design

MHI, Japan design

Russian design
# Steam boiler general definitions*

<table>
<thead>
<tr>
<th>Type</th>
<th>Superheater temperature (°C)</th>
<th>Superheater pressure bar</th>
<th>Net Efficiency for typical hard coal %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Critical</td>
<td>&lt;540</td>
<td>&lt;221</td>
<td>&lt;35</td>
</tr>
<tr>
<td>Supercritical</td>
<td>540-580</td>
<td>221-250</td>
<td>35-40</td>
</tr>
<tr>
<td>Ultra supercritical</td>
<td>580-620</td>
<td>221-250</td>
<td>40-45</td>
</tr>
<tr>
<td>Advanced Ultra supercritical</td>
<td>700-725</td>
<td>221-350</td>
<td>45-52</td>
</tr>
</tbody>
</table>

* Based on IEA COAL data
The fuel is burned in the boiler furnace and the flue gas is generated.

Primary air is mixed with fuel and combusted in the furnace.

Igniter provides flame ignition.

Secondary air addition in the furnace helps for complete combustion and flame stability.

Furnace effective projected surfaces and water walls help in heat transmission.

In the furnace bottom hopper is provided to collect inorganic compounds of fuel separated after combustion.
All of the components that are under steam or water pressure.
The walls are of membrane type and the furnace is cooled with boiling water.

Furnace wall tubes are spaced on close centres to keep membrane temperatures and thermal stresses within limits.

The membrane panels are composed of tube rows spaced on centres wider than a tube diameter and joined by a membrane bar securely welded to the adjacent tubes.

At furnace openings, tubes are profiled to match the openings.
Design factors

- The Size of the furnace varies with type of fuel burned.
- Allowable heat loading
- EPRS Surface
- Plan area
- Volumetric surface
- Burner clearance
- Gas firing furnace size is the smallest
- Oil firing furnace is bigger than gas firing furnaces.
- Coal firing boiler furnace is bigger than oil firing boiler
Supercritical Flow Schematics: Vertical Wall versus Spiral Wall
- Reduced number of tubes with pitch.
- Increased mass flow.
- Mass flow rate can be selected by number of tubes.
## Spiral vs. Vertical Wall Comparison

<table>
<thead>
<tr>
<th>Spiral</th>
<th>Vertical Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral Furnace System Applicable for all size units</td>
<td>Vertical Furnace Wall System Limited to larger capacity units (&gt;600 MW depending on fuel)</td>
</tr>
<tr>
<td>Benefits from averaging of lateral heat absorption variation (each tube forms a part of each furnace wall)</td>
<td>Less complicated windbox openings</td>
</tr>
<tr>
<td>Simplified inlet header arrangement</td>
<td>Traditional furnace water wall support system</td>
</tr>
<tr>
<td>Large number of operating units</td>
<td>Elimination of intermediate furnace wall transition header</td>
</tr>
<tr>
<td>Use of smooth bore tubing throughout entire furnace wall system</td>
<td>Less welding in the lower furnace wall system</td>
</tr>
<tr>
<td>One material utilized throughout entire waterwall system</td>
<td>Easier to identify and repair tubes leaks</td>
</tr>
<tr>
<td>No individual tube orifices – Less maintenance &amp; pluggage potential</td>
<td>Lower water wall system pressure drop thereby reducing required feed pump power</td>
</tr>
</tbody>
</table>
Superheaters

- In furnace radiant zone SH are installed and they absorb heat by radiation and convection
- The second pass SH absorb heat mainly by convection
- Primary SH are located in the convective zone
- In large high pressure boilers SH surface generally forms the furnace outlet plane
- The gas temperature entering the SH must be high enough to generate the desired SH temperature
- Reasonable amount of heating surface and selection of materials suitable for withstanding high temperatures are required
- To optimise superheater design, the furnace may also incorporate widely spaced steam cooled platen SH surface
Reheater tubes

- Reheaters are placed after the secondary superheaters.
- The steam extracted from the HP turbine outlet is passed through the reheater inlet.
- Reheated steam is sent to IP inlet.
- Reheaters are provided with a single stage desuperheater to control the RH steam outlet temperature.
Screen tubes

- The screen tubes are widely spaced to provide to prevent ash and slag plugging and fouling.
- Screen tubes facilitate cleaning arrangement for dirty fuels.
- Screen tubes receive heat by radiation in the furnace.
- And receive heat by convection from the combustion gases passing through them in the second pass.
Vertical or Pendent type superheaters

**Vertical superheaters**

- These are located with tubes placed in the vertical orientation
- Frequently located just above the furnace
- Often placed in a co-current direct ion with the gas path to moderate heat pick-ups
- Top supported
Horizontal tube banks

- The tubes are located horizontally and placed in arrays normally in convective zones.
- These are generally found in the rear pass of the boiler.
- Heat transfer at individual sections are varying due to change in flue gas properties and steam properties.
- Allow self draining.
Sliding Pressure Operation

Pressure operation mode at boiler outlet

1. Constant Pressure Operation
2. Modified Sliding Pressure Operation
3. Pure Sliding Pressure Operation
Sub vs. Supercritical Cycles

Lower Fuel Consumption and Emissions/kWh with SC Cycle

Plant Heat Rate Improvement

50°F ≈ 1.4 % improvement

- 600/620°C
- 600/600°C
- 580/600°C
- 560/560°C
- 540/540°C

Subcritical                  Supercritical  and   UltraSupercritical
When Water is heated at constant pressure above the critical pressure, its temperature raises and latent heat addition does not happen.

Water is in supercritical state and hence separation of water and steam does not required.

The actual location of the transition from liquid to steam in a once through super critical boiler is free to move with different condition: Sliding Pressure Operation.

For changing boiler loads and pressure, the process is able to optimize the amount of liquid and gas regions for effective heat transfer.

Better reductions of emission can be achieved. Eg. For each Kwh of electricity generated: Superior Environmental 1% rise in efficiency reduce the CO2 emission by 2-3%.

Fuel cost saving can be achieved and hence it has economical benefits.

Helps to achieve with operating flexibility.

Reduces the relative boiler size / MW.

Can be used to reduce Start-Up time.
There are a number of design characteristics associated with supercritical boilers that are different to those associated with sub-critical units and include the following:

- water quality
- improved heat transfer
- use of smaller tube sizes
- use of steam separators instead of drums
- reduced furnace size
KEPCo Yonghung Units 1,2
800MW Sliding Pressure Supercritical

Unit $M_{we}$: 800

Max. Continuous Rating: 5,324,168 lb/hr

SH Outlet Press: 250 bar

SH Outlet Temp: 568°C

RH Outlet Temp: 568°C

Fuel: Australian Bituminous
Jinzhushan-3  660 MW supercritical boiler

- Designed on B&W VTUP® Technology
- SH steam capacity  1900 ton/hr
- SH steam Pressure  254 bar
- SH steam Temperature 571°C
- Reheated steam at 569°C
- “Heater Above Reheat Point” (HARP) steam cycle is used, providing feedwater to the boiler at 289°C

Source : Technical Paper BR-1849, Babcock & Wilcox
NTPC- Sipat 660 MW Boiler, India

Source: NTPC
Opole Power Plant, Poland
2x 900MW Supercritical Units

- Once-through tower type PC boiler equipped with:
  - low NOx PC firing system equipped with:
    - tangential system of jet-type burners,
    - SOFA nozzles,
    - SCR system – secondary method of deep reduction of NOx,
    - ESP – dedusting of flue gas,
    - FGD system – wet method.
  - SH steam parameters (2455 TPH/597 °C / 275 bar)
  - RH steam parameters (609 °C / 5.8 bar), unit efficiency at the level of 45.5%.

Source: Wieslaw Zablocki - RAFAKO S.A., Krzysztof Burek - RAFAKO S.A.
750 MW Lünen coal-fired power plant, Germany

- International low-sulphur bituminous coal delivered by river barge.
- The estimated project cost is €1.4 billion—equivalent to an installed cost of $2,547/kW (2009 $).
RDK- 8, Karlsruhe, EnBW 912 MW hard coal-fired power plant Germany

<table>
<thead>
<tr>
<th>BOILER TECHNICAL DATA (100% LOAD)</th>
<th>MAIN STEAM</th>
<th>REHEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam flow (t/h)</td>
<td>2347</td>
<td>1951</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>285</td>
<td>59</td>
</tr>
<tr>
<td>Temperature (°C/°F)</td>
<td>603/1117</td>
<td>621/1150</td>
</tr>
<tr>
<td>Feedwater temperature (°C/°F)</td>
<td>305/581</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>Imported bituminous coal</td>
<td></td>
</tr>
<tr>
<td>NOx emissions</td>
<td>100 mg/mN³ with SCR</td>
<td></td>
</tr>
<tr>
<td>CO emissions</td>
<td>150 mg/Nm³</td>
<td></td>
</tr>
</tbody>
</table>

Source: Alstom Publications
Typical Boiler Materials
Advanced alloy steel materials

Source: US program on Advanced supercritical alloy materials, presented to IEA clean coal workshop, 2012
### Material difference between sub and supercritical boilers

<table>
<thead>
<tr>
<th></th>
<th>Subcritical boilers</th>
<th>Super-critical boilers</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Furnace</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lower Furnace</strong></td>
<td>Vertical tube</td>
<td>Spiral tube furnace (lower)</td>
<td>for SC, spiral tube walls required to ensure cooling water wall under sliding pressures</td>
</tr>
<tr>
<td></td>
<td>Carbon/Ferritic alloy (eg 210C/T12)</td>
<td>Ferritic alloy (eg T12/T22)</td>
<td>for SC, higher fluid temperatures require higher grade materials</td>
</tr>
<tr>
<td><strong>Upper furnace</strong></td>
<td>Vertical tube</td>
<td>Vertical tube</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carbon/Ferritic alloy (eg 210C/T12)</td>
<td>Ferritic alloy (eg T12)</td>
<td>for SC, vertical tubes provide sufficient cooling in the upper furnace</td>
</tr>
<tr>
<td></td>
<td>Carbon steel (eg 210C)</td>
<td>Carbon steel (eg 210C)</td>
<td>No difference</td>
</tr>
<tr>
<td><strong>Low temperature SH</strong></td>
<td>Ferritic alloy (eg T22/T91)</td>
<td>Ferritic alloy (eg T22/T91)</td>
<td>No difference</td>
</tr>
<tr>
<td><strong>Intermediate SH</strong></td>
<td>Ferritic alloy (eg T22/T91)</td>
<td>Ferritic alloy (eg T22/T91)</td>
<td>No difference</td>
</tr>
<tr>
<td><strong>Finishing SH</strong></td>
<td>Ferritic alloy (eg T91)</td>
<td>Ferritic alloy/stainless (eg T91/347)</td>
<td>for SC w/ 540C, no difference. For SC w/ 565C, stainless req'd</td>
</tr>
<tr>
<td><strong>Low temperature RH</strong></td>
<td>Carbon steel (eg 210C)</td>
<td>Carbon steel (eg 210C)</td>
<td></td>
</tr>
<tr>
<td><strong>Finishing RH</strong></td>
<td>Ferritic alloy (eg U90)</td>
<td>Ferritic alloy/stainless (eg T91/304)</td>
<td>for SC w/ 540C, no difference. For SC w/ 565C, stainless req'd</td>
</tr>
</tbody>
</table>
Comparison of Ash Characteristics for HFO & Coal

Coal fuel & ash
- Fuel CV is typically 23 to 28 MJ/kg
- Ash typically comprises 10 to 25% of ‘as received’ fuel content
- Sulphur and Chlorine rarely form more than 2.5% of fuel content
- Ash tends to comprise of Silica and high melting point oxides
- Ash can be removed from boiler surfaces using soot blowing
- Ash generally takes on alkali characteristics

Crude/HFO & their ash
- Fuel CV is typically 40 to 42 MJ/kg
- Ash only comprises 0.1% of fuel content
- Sulphur content can be as high as 7% but is typically 3%
- Contains metal compounds of Vanadium & Sodium that act as corrosion catalysts
The fundamental differences are the need for make up and condenser water polishing in supercritical plant and the reduction in throughput equivalent to the blow down quantities in sub-critical plant.

<table>
<thead>
<tr>
<th>FW property measured</th>
<th>Sub-critical, Drum Boilers</th>
<th>Supercritical, Once Through Boilers</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>9.2 to 9.5 (AVT), or 8.8 to 9.2 (OT)</td>
<td>9.2 to 9.8 (AVT), or 8.4 to 9.8 (OT)</td>
</tr>
<tr>
<td>Acid Conductivity, µS/cm</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Conductivity (NH3 dosing only), µS/cm</td>
<td>4.3 to 8.6 (AVT), or 1.7 to 4.3 (OT)</td>
<td>4.3 to 8.5 (AVT), or 0.7 to 2.8 (OT)</td>
</tr>
<tr>
<td>Oxygen as O2, µg/kg</td>
<td>5 to 20 (AVT), or &gt; 30 (OT)</td>
<td>5 to 20 (AVT), or 30 to 150 (OT)</td>
</tr>
<tr>
<td>Silica as SiO₂, µg/kg</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Iron as Fe, µg/kg</td>
<td>&lt; 10</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Sodium as Na, µg/kg</td>
<td>Not Applicable.</td>
<td>&lt; 2</td>
</tr>
</tbody>
</table>
The Use of Smaller Tube Sizes

Most code formula for calculation of minimum tube thickness are similar to:

\[ t_{min} = \frac{P \cdot d_o}{(2 \cdot f + P)} \text{ or } \frac{P \cdot d_i}{(2 \cdot f - P)} \]

The table below gives some examples of thickness variations for 50 mm tubes at typical sub-critical and supercritical conditions:

### Comparison of minimum wall thickness requirements for 50 mm tubes in T22 and T91 materials at 540°C & 200,000 hours

<table>
<thead>
<tr>
<th></th>
<th>T22 or 10CrMo9-10</th>
<th>T91 or X10CrMoVNb9-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>At Sub-critical 160 bar, ( t_{min1} )</td>
<td>6.41 mm</td>
<td>2.76 mm</td>
</tr>
<tr>
<td>At Super-critical 250 bar, ( t_{min2} )</td>
<td>9.34 mm</td>
<td>4.19 mm</td>
</tr>
</tbody>
</table>

### Comparison of metal conductivity and parameter \( t/k \) for T22 and T91 materials at 540°C

<table>
<thead>
<tr>
<th></th>
<th>Conductivity (k), W/m K</th>
<th>Parameter ( (t/k) ), m² K / kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>T22 or 10CrMo9-10</td>
<td>35.41</td>
<td>0.181</td>
</tr>
<tr>
<td>T91 or X10CrMoVNb9-1</td>
<td>27.42</td>
<td>0.153</td>
</tr>
</tbody>
</table>
Table notes: The above table includes for a 4.5% annual inflation rate over 30 years, a local income tax rate of 35%, initial electricity value of 0.05 $/kWh, initial fuel cost of 1.42 $/GJ, initial desalinated water cost of 4 $/1000 gal, and payment of CAPEX is from Equity.
Boiler

Emissions control arrangement

Source: Alstom publications
Emission control arrangement

Source: Wieslaw Zablocki - RAFAKO S.A., Krzysztof Burek - RAFAKO S.A.
1. Basic Boiler system
2. Dust collection
3. Flue Gas Recirculation (FGR) for reducing NOx production
4. Low NOx burners & Over fire air systems
5. Flue Gas Desulphurisation (FGD) for removing SOx
6. Selective Non-Catalytic Reduction (SNCR) for removing some of the NOx in the furnace
7. Selective Catalytic Reduction (SCR) for removing NOx
Legislative requirements

- Construction in line with European standards
- Pressure equipment directive (PED)
- Industrial Emissions Directive (IED)
- Ash requirements – Low unburned carbon in Ash
- Design standards – EN 12952 (Most of the sections), ASME
Conclusions

- Based on current International fuel costs the choice of supercritical technology should provide a payback within approximately 15 years.

- Supercritical & Ultra Supercritical technology offer efficiency improvements between 0.5% and 12%.

- They offer CO$_2$ and SO$_x$ emission reductions between 2% and 4%.

- Reduced space requirement for similar electricity outputs.

- They have better ability to respond to load changes with lower fatigue risk to pressure part components than subcritical options.

- Material development would help in reducing the overall costs of the plant.
Thank you
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