Materials Issues in Co-fired and Oxy-fired Combustion Power Plants

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Materials Issues in Co-fired and Oxy-fired Combustion Power Plants

Outline

- Background
- Fuels & compositions
  - Coal vs biomass
- Heat exchangers
  - Operating requirements
- Biomass/coal co-firing
  - Gas compositions
  - Deposit compositions
  - Fireside corrosion
- Oxy-fuel firing
  - Differences with conventional systems
- Summary
Background

Issues for solid fuel power generation systems:

- Environmental performance
  - CO₂ emissions
  - SOₓ, NOₓ, particles, …
- Efficiency
- Fuel flexibility
  - Fuel supply
  - Fuel availability
- Cyclic operation
- Reliability, availability, maintainability, operability
- Cost of electricity generated
Options for Solid Fuel based Advanced Power Generation Systems

- Increase in generating efficiencies
  - Higher operating temperatures / pressures in steam & gas turbines
- Fuel switching, e.g.
  - Replace coal by natural gas
  - Replace coal with biomass – co-firing
- Capturing and storing CO₂
Track 1 approaches, available now, include improved efficiency by introduction of advanced supercritical boiler/turbine technology and biomass co-firing (substitution of up to 20% of the coal fuel by biomass which is CO₂ neutral).

Track 2 approach, carbon dioxide capture and permanent underground storage, is necessary to achieve much larger reductions, up to 95%.
Materials Issues in Advanced Solid Fuel Power Generation Plant

More challenging component operating conditions:
- Higher operating temperatures / pressures
- Cyclic operation
- Wider range of fuels

Resulting materials issues:
- Fireside corrosion / hot corrosion
- Steamside oxidation / scale spallation / erosion
- Dewpoint (aqueous) corrosion
- Creep
- Fatigue (LCF, HCF, TMF, ..)
- Alloy / coating selection
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Potential solid fuels

• Coal
  • Locally mined
  • World traded

• Biomass
  • Specifically cultivated biomass (‘energy crops’) - e.g.: coppiced willow, miscanthus
  • Waste biomass – e.g. straws, wood waste, forestry residues
  • World traded biomass – e.g. palm nut / olive / almond residues, pelletised wood, cereal co-product (CCP)

• Waste
  • Sewage sludges; animal wastes
  • Municipal solid waste (MSW)
  • Refuse derived fuel (RDF)
  • Solid recovered fuel (SRF)
Relationships between C, H & O for solid fuels

![Graph showing the relationships between C, H, and O for different types of fuels. The graph includes data for coals, lignite, peat, and biomass, with different areas and colors representing different atomic ratio ranges.](image-url)
Cl vs S for biomass & coals

Fuel Sulphur (%) vs Fuel Chlorine (%)

- Coals
- Biomass

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Fuel composition variability

- Biomass
  - Plant types
  - Growth location (country, soil type)
- Fast vs slow growing
- Harvest time
- Post-harvest storage / treatment
- Batch to batch as-delivered

- Coals
  - Coal type
  - Origin (e.g. UK vs South America)
Minor / Trace Element Concentrations

- Also elements bound in different ways in biomass & coal
  - Elements in coal can be bound in stable mineral matter
  - Elements in biomass more readily releasable (water / acid solubility)
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PULVERISED FUEL SYSTEMS

- Coal-fired
  - Older plants ~540-560°C / ~160 bar steam
  - Current plants ~600-620°C / ~290 bar steam
  - Future plants – steam temperatures
    - 650°C - COST
    - 700°C - EU THERMIE
    - 750°C - USA
- Co-fired coal and biomass
  - New fuel compositions/mixes
  - Current and future steam conditions
- Oxy-fuel fired
  - New basic combustion gas composition
  - Current and future steam conditions
  - Biomass co-firing
Superheater tubing – cross-section through tube wall

- Fireside
- Steam-side
- TUBE WALL
- Load Bearing Thickness
- Corrosion Allowance
- Oxidation Allowance
- Hot gas flow

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Heat exchanger life, corrosion allowance, acceptable corrosion rates

Life (hours)

Corrosion rate (µm/1000 hour)

Corrosion Allowance

- 1 mm
- 1.5 mm
- 2 mm
- 2.5 mm
- 3 mm
- 3.5 mm
Comparison of corrosion data for 347H and 347HFG with coal and straw firing (plant data) and co-firing (pilot plant data) (median data)

Source: COST522 / 538
Plant operating conditions for heat exchanger tubes

- Fuel: coal / biomass
- Oxidant: air / oxygen
- Gas stream characteristics:
  - Gaseous species – e.g. $\text{SO}_2$, $\text{HCl}$, $\text{O}_2$, $\text{CO}_2$, $\text{H}_2\text{O}$, $\text{NO}_x$, $\text{N}_2$
  - Vapour species – e.g. $\text{Na}$, $\text{K}$
  - Particles
    - From ash in fuel
    - Condensed vapour species
- Gas temperature
- Heat exchanger characteristics:
  - Water / steam temperature (& pressure)
  - Metal temperature (& heat flux)
  - Deposit
    - rate of formation
    - composition
Flow Diagram for Component Life Modelling

- Component Specification
- Operating Conditions
- Fuel Spec. & Reactor System
- Thermal Model
- Aerodynamic Model
- Thermochemical Model
- Transport & Deposition Models
- Corrosion & Erosion/Corrosion Models
- Mechanical Property Data
- Life Predictions
  - Contaminant effects
  - Operating condition effects

Component design & life criteria
- Metal surface temperature
- Alloy specification
- Deposition flux & composition
- Damage rates
- Gas flow rate
- P & T distributions
- Inlet & outlet gas P & T
- Contaminant levels & species
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Sensitivity of SO$_2$ vs HCl to changes in cereal co-product (CCP) co-firing with two coals

- **UK coal (Daw Mill) + CCP**
- **South American coal (El Cerrajon) + CCP**

Increase in co-firing

- 100% UK.
- 100% S.Am.
Sensitivity of SO$_2$ vs HCl to changes in cereal co-product (CCP) or typical wheat straw co-firing with two coals compared to example biomass.

- UK coal (Daw Mill) + straw (wheat, typical)
- UK coal (Daw Mill) + CCP
- South American coal (El Cerrajon) + straw (wheat, typical)
- South American coal (El Cerrajon) + CCP
- Biomass (examples)
Deposition on Superheater / Reheater Tubing

Deposition mechanisms:

**Particles:**
- Direct inertial impaction
- Thermophoresis
- Eddy diffusion
- Brownian

**Vapour:**
- Direct condensation
- Condensation on particles

Vapour species

Condensation onto solid particles & aerosols

Solid particles & aerosols

Coarse particles stick

Vapours, SOx & HCl diffuse in porous deposits

Condensation into deposit

Thermophoresis of fine particles

Corrosion

Water / steam

Heat transfer
Fuel derived deposit compositions

Deposit compositions:
• Si-Al-O compounds
  • can fix Na, K if particle temperatures high enough
  • Al only if coal co-fired
• Ca/Mg carbonates / sulphates / chlorides
• Na / K sulphates / chlorides
• Fe sulphates / chlorides / oxides / sulphides
• Phosphates – from biomass

Important factors
• Minerals in fuels
• Balance between elements

Corrosion aggravated by:
• Low melting point deposits
• High chloride deposits
Effect of fuel S/Cl balance on deposit compositions

Dependence of deposit chlorine content on fuel sulphur and alkali chloride contents
[US DoE Research]

Appearance of chlorides in deposits as a function of maximum alkali chloride, fuel sulphur and % straw (on thermal basis)
[EU research]
Possible fireside corrosion mechanisms in sodium chloride / sulphate dominated deposits

Chloride based mechanism

- HCl
- O₂
- Cl₂
- FeCl₂
- FeCl₃
- Fe₂O₃
- FeO
- FeS
- Tube metal

Sulphate based mechanism

- SO₂ + O₂ + H₂O
- SO₂ + O₂
- Na₂SO₄
- Na₂S₂O₇
- Na₂O
- NaHSO₄
- FeCl₂
- Cl₂
- FeCl₃
- Fe₂O₃

Deposit

Corrosion products
Alkali sulphate dominated corrosion regimes in combustion gases

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Oxy-fuel firing

Plant options:
- Purity of oxygen
- Location of flue gas recycle take-off point
  - Before any gas clean-up
  - After particle removal
  - After flue gas desulphurisation
- Further gas clean-up before recycle
  - Dry primary combustion gas stream
  - Dry secondary or tertiary combustion gas streams

*Have direct effect on component operating conditions*
Schematic diagram of Oxy-fired combustion system

Source: Vattenfall
Gas compositions
- UK vs S American coals
- air vs oxy-fired with fuel gas recycle taken before FGD
Oxy-firing: fireside materials issues

- Gas composition
  - Much higher SOx and HCl than conventional plants possible
    - ~4-5 times higher if recycle before FGD system
  - High CO₂ and steam levels (at same O₂ levels as conventional plants)
- Higher metal operating temperatures of heat exchangers
  - Higher efficiencies needed to counter CO₂ capture penalties
- Deposition
  - Compositions and formation rates changed by
    - gas compositions
    - metal surface temperatures
- Fireside corrosion rates – depend on:
  - Gas composition
  - Deposit composition and formation rate
  - Metal temperatures
  - Enough differences to cause mechanism change?
- Dewpoint (aqueous) corrosion
  - Changes in gas composition can significantly increase dewpoint temperatures
SUMMARY

Many materials issues are being raised by the on-going developments of solid fuel fired power systems as a result of the use of:

- Wider range of fuels with higher contaminant levels
- Higher component operating temperatures
- Novel component operating environments
- Novel environments resulting from fuel and/or oxidant changes have a particular affect on the fireside corrosion of components
- Increased operating temperatures and plant cycling affect mechanical requirements, as well as fireside corrosion and steamside oxidation

Current materials R&D activities focused on:
- Materials selection – alloys and/or coatings
- Component lives / reliability
Thank you for your attention