OxyCoal™ burner testing to develop models for oxyfuel combustion

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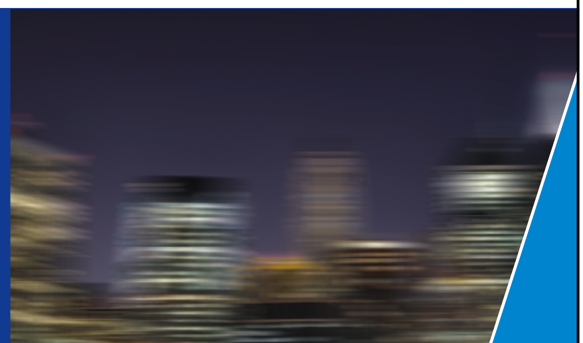


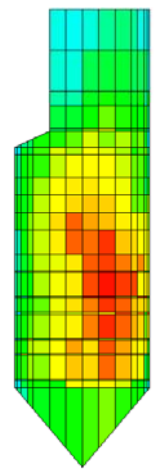
Outline

- Doosan Thermal Performance Assessment Tools
  - SteamGen
  - HotGen
- Vattenfall Europe Technology Research GmbH Oxyfuel Pilot Plant (OxPP)
  - Doosan 30MWt OxyCoal™ Burner
  - Operational performance
  - Combustion performance
  - Themal performance
- Fundación Ciudad de la Energía Technology Development Centre for CO_2 Capture (es.CO_2)
  - 20MWt Pulverised Coal (PC) Boiler
  - 4-off 5MWt Burners, Opposed Wall Firing
  - Next steps
- Conclusions

Design Tools – Furnace Thermal Performance (HotGen)

HotGen uses Hottel's zone method to predict furnace thermal performance

- Predicts overall and local performance (FEGT, heat to walls, heat to platens, heat flux profiles, etc.)
- Furnace volume divided into discrete blocks – "zones"
  - Temperature and physical properties are implicitly assumed to be uniform within each zone
  - Smaller zones better justify this assumption
- Energy balance solved for enthalpy for each zone
  - Radiation, convection, heat release in zone
  - Gas absorption (extinction) coefficient defines fraction of radiant heat absorbed within zone vs. fraction passing through (optical thickness)
- Monte Carlo approach used to calculate radiant heat transfer between zones
  - Discrete packages of energy from each zone (of random strength and direction) are tracked through furnace volume
- Sound theoretical basis
  - Implicitly handles thermal radiation issues (furnace size, impact of flyash, etc.)
  - All inputs have physical significance (model is truly predictive, unlike simpler semi-empirical models)
  - Can accommodate oxyfuel firing
- Robust
  - Can simulate all the main technologies (wall firing, downshot firing, tangential firing)
  - Short run times with no convergence problems (unlike CFD)



Absorbed Heat Flux to Furnace Side Wall (kW/m^2)

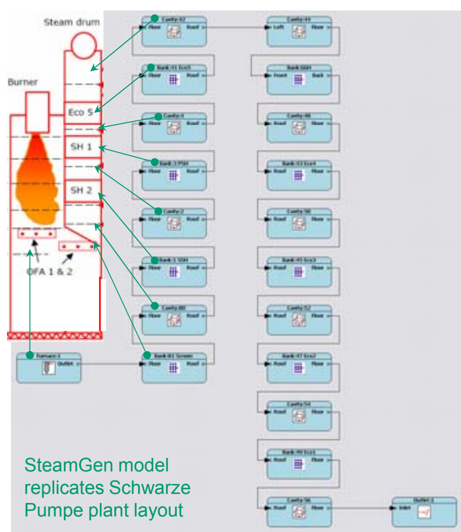
Design Tools – Boiler Thermal Performance (SteamGen)

Predicts furnace and boiler thermal performance

- Overall Furnace Performance – FEGT, heat to walls, heat to platens
  - Uses simple furnace model (HotGen is considerably more sophisticated)
- Overall Boiler Performance – bank absorptions, gas temperature at bank exit
  - Model accommodates spray, split rear pass, and FGR steam temperature control methods
  - Detailed representation of plant – banks, cavities, screens, enclosures, sling tubes, etc.
  - Accurately describes gas and steam paths (network)

Design and performance modes

- Performance mode
  - Calibrate model to plant data and derive bank performance factors
  - Feed back plant operating experience into design process
  - Quantify operating experience for novel scenario's, e.g. oxyfuel operation
- Design mode
  - Specify factors and predict performance



Oxyfuel Pilot Plant Project Schwarze Pumpe

The Oxyfuel Pilot Plant (OxPP) tests aim to improve the oxyfuel combustion process as well as establish a better understanding of the behaviour of individual components within the process chain.

- Doosan joined the Technology Partnership for the Oxyfuel Pilot Plant (OxPP) project
  - Agreement signed between Vattenfall Europe Technology Research GmbH and Doosan in December 2010
- Doosan was responsible for providing an alternative burner (30MWt OxyCoal™ burner) for testing on the pilot plant

- The purpose of the pilot plant was to validate engineering, to investigate and better understand the dynamics of oxyfuel combustion, and to demonstrate the capture technology

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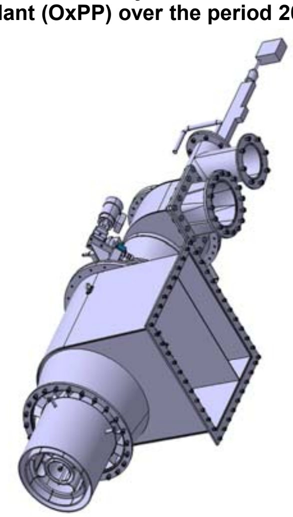
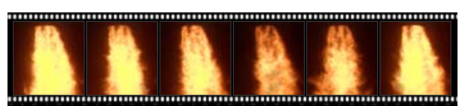
Oxyfuel Pilot Plant Project Schwarze Pumpe

Doosan's 30MWt OxyCoal™ burner was operated for close to 2800 hours in the Oxyfuel Pilot Plant (OxPP) over the period 2011~2012





Air Firing Oxy Firing

- Automatic control logic developed, demonstrated safe and smooth transitions between air and oxy firing, and vice versa.
- Stable anchored flame maintained at all stages of the transition
- 300 hours operation of the 30MWt OxyCoal™ burner on air firing.
- 2500 hours operation of the 30MWt OxyCoal™ burner on oxy firing.
- Steady oxy firing operation for extended periods - a requirement for parallel test measurements.

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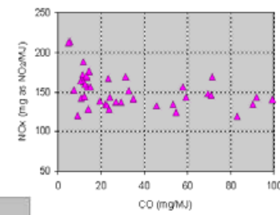
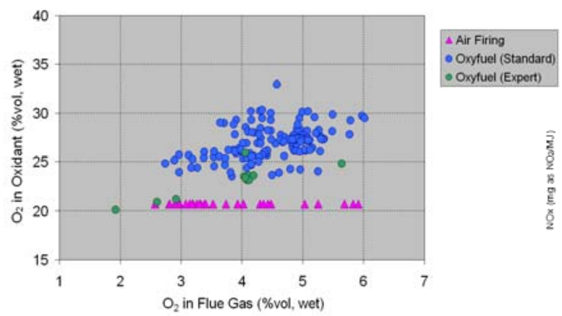
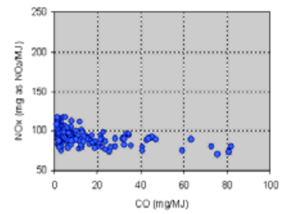
Oxyfuel Pilot Plant Project Schwarze Pumpe

The 30MWt OxyCoal™ burner demonstrated good flame stability over a wide range of operating conditions, while maintaining low levels of NO_X and CO.

- Combustion performance optimised to achieve set targets.
  - Excess O_2 < 3 vol% (wet)
  - NO_X < 250 mg/Nm³ (air) < 800 mg/Nm³ (oxy)
  - CO < 50 mg/Nm³ (air) < 100 mg/Nm³ (oxy)







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Thermal performance assessment

- Two operating periods considered here
  - Air firing
    - 8 hour period, starts 20 hours after boiler cleaning cycle initiated
  - Oxyfuel firing
    - 24 hour period encompassing a boiler cleaning cycle and the 8 hours preceding / following the boiler cleaning
- Further periods of steady and non-steady operation to be analysed
  - Large data set required to provide confidence in analysis findings
- Analysis undertaken using Doosan's SteamGen boiler performance model
  - Provides furnace boundary conditions for subsequent HotGen & CFD analysis
  - Analysis considers all surfaces and cavities/enclosures in boiler
    - Presentation shows results for furnace and one convective tube bank

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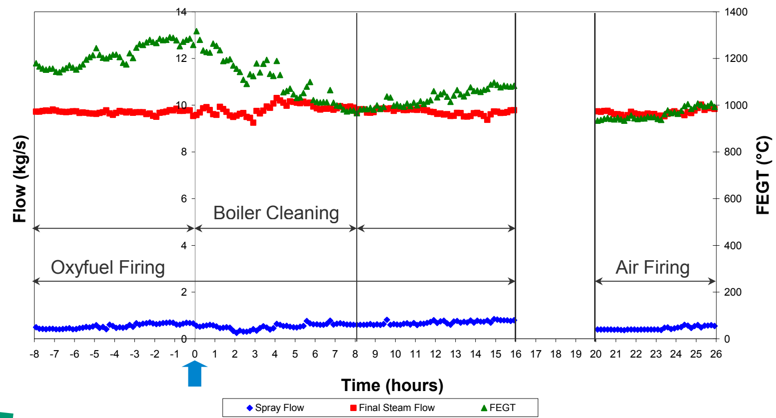
Measured data shows consistent plant behaviour throughout operation

- At constant thermal load (final steam flow)……
  - FEGT increases over time (deposit build-up), reduces during cleaning cycle
  - Spray flow increases with increasing FEGT
    - Higher FEGT indicative of lower heat to furnace walls, increased heat to convective pass



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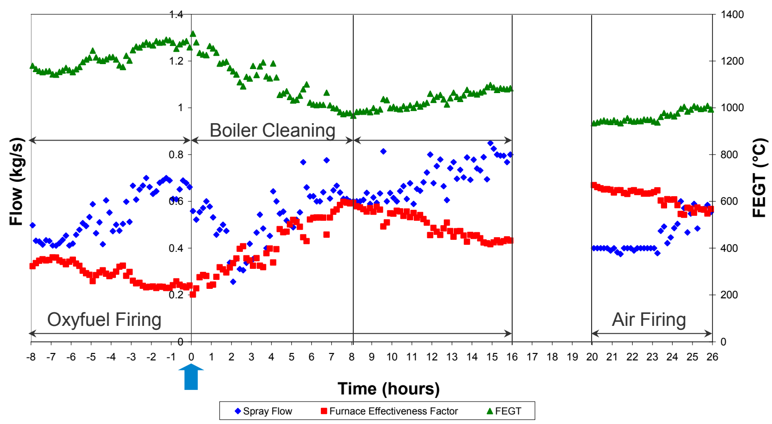
Thermal performance analysis shows consistency between SteamGen model and plant

- During boiler cleaning FEGT reduces, derived furnace effectiveness increases
  - Derived furnace effectiveness reduces with time, in-line with observed FEGT, due to build-up of deposits
  - Analysis shows spread of furnace effectiveness for “clean” and “dirty” furnace
  - Analysis suggests greater furnace effectiveness for air firing cf. oxyfuel
  - …….But analysis is for a limited data set – insufficient to derive “design guidelines” for new plant



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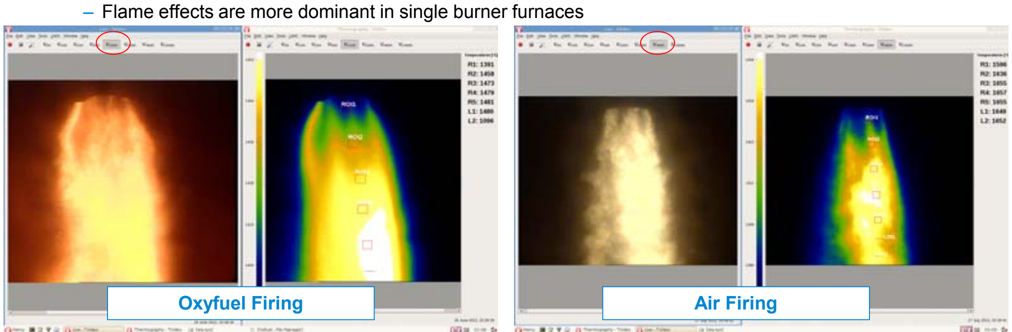
The higher furnace effectiveness for the air firing test is probably due to the flame

- Causes of increased furnace performance include…..
  - Cleaner furnace
  - Flame temperature
    - Air firing has appreciably higher flame temperature (~200°C), leading to increased radiation to furnace walls
  - Flame luminosity
    - Air firing has a brighter flame (note reduced exposure time for air firing photo!), also leading to increased radiation to furnace walls
- Observations relate to these specific test periods; further analysis needed to develop "rules"
  - Flame effects are more dominant in single burner furnaces



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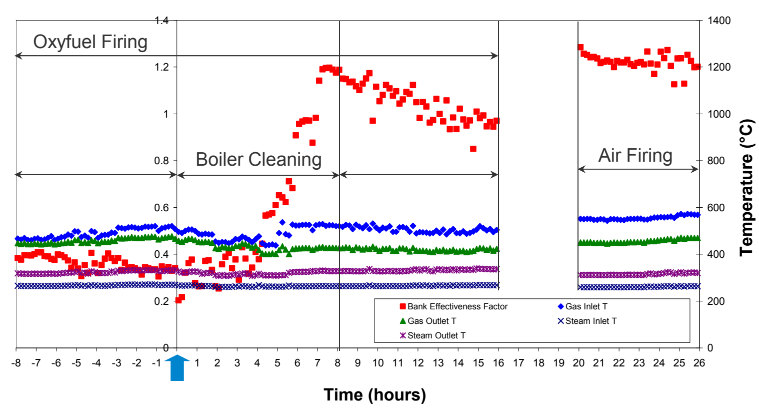
Oxyfuel Pilot Plant Project Schwarze Pumpe

Thermal performance analysis shows consistency between SteamGen model and plant

- During boiler cleaning, derived convective bank effectiveness factor increases, and gas side ΔT increases indicating greater heat pick-up
  - Derived bank effectiveness reduces with time, in-line with observed ΔT, due to build-up of deposits
  - Analysis shows spread of furnace effectiveness for "clean" and "dirty" convective bank
  - Analysis suggests greater bank effectiveness for air firing cf. oxyfuel
  - …….But analysis is for a limited data set – insufficient to derive "design guidelines" for new plant



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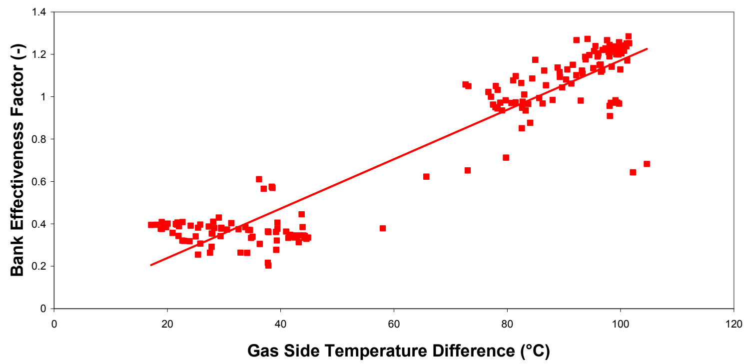
Convective bank effectiveness factor correlates with gas-side ΔT

- SteamGen model takes account of different firing mode and variations in bank inlet conditions
  - Air firing test has different flue gas composition and flow (impact on gas-side htc)
  - Air firing test has higher inlet gas temperature to bank (in spite of lower FEGT)



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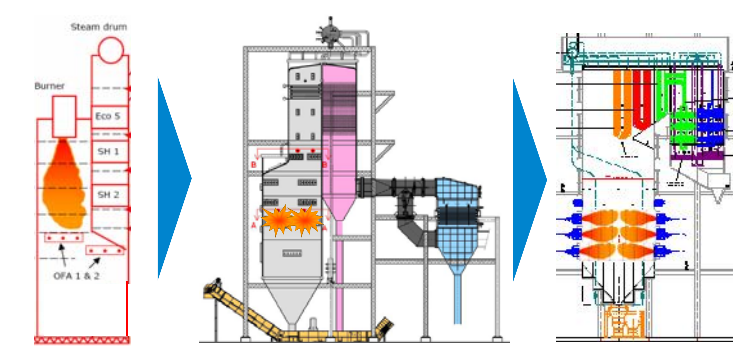
Limitations of Large Test Facilities

Test furnaces often do not replicate the radiation processes in utility plant

- Specific issues include
  - Realistic mean beam lengths (test furnaces are an order of magnitude smaller)
  - Pendant (radiant) superheaters (test furnaces generally do not have pendants, and avoid radiant surfaces)
  - Volumetric utilisation of the furnace (combustion zone in single burner furnaces vs. multi-burner furnaces)



Schwarze Pumpe Single burner Convective SH Small furnace	CIUDEN Multi-burner (4) Radiant SH Small furnace	Plant Multi-burner (36) Radiant SH Large furnace

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Schwarze Pumpe vs. es.CO_2

CIUDEN's es.CO_2 test facility complements Schwarze Pumpe

Vattenfall

- Oxyfuel Pilot Plant (OxPP)
  - 1 x 30MWt burner
  - Down fired
  - Pre-dried lignite
  - Radiant natural circulation furnace
  - Convective superheater
  - Convective economiser
  - Spray attemporation
  - Demonstration of near full-scale burner

CIUDEN

- Technology Development Centre for CO_2 Capture (es.CO_2)
  - 4 x 5MWt burners
  - Opposed wall fired
  - Pre-dried bituminous coal
  - Radiant natural circulation furnace
  - Radiant + Convective superheaters
  - Convective economiser
  - Spray attemporation
  - Investigation of burner interaction
  - Investigation of furnace heat transfer in a realistic arrangement

Doosan Engagement with CIUDEN

Collaborative activities

- Doosan and CIUDEN are currently partners in the European Union (EU) FP7 funded project "Reliable and Efficient Combustion of Oxygen/Coal/Recycled Flue Gas Mixtures" ("RELCOM")
  - The RELCOM project is designed to undertake a series of applied research, development and demonstration activities involving both experimental studies and modelling work to enable full-scale early demonstration oxyfuel plant to be designed and specified with greater confidence as well as providing improved assessment of the commercial risks and opportunities
  - CIUDEN will undertake tests on the es.CO_2 Facility's 20MWt PC-fired oxyfuel boiler, including baseline air firing and oxyfuel firing tests
- Doosan and CIUDEN are partners in the Extended Operational Data Gathering agreement for the purpose of carrying our further detailed analysis of the es.CO_2 PC boiler

Next steps

- Furnace (HotGen) and boiler (SteamGen) thermal performance analysis of the es.CO_2 PC boiler
  - Expand experience base (different boiler, multi-burner furnace, coal rank effect)
  - Increase confidence in thermal performance predictive capability

Conclusions

Experience at large scale leads to greater confidence in the design of oxyfuel plant

- Combustion testing of Doosan's 30MWt OxCoal^{TM} burner at Vattenfall's OxPP Schwarze Pumpe pilot-plant demonstrated
  - Good flame stability, including during air↔oxyfuel transitions
  - Achievement of required NOx and CO emissions
  - Flexible operation, automated control logic
- Thermal performance analysis of two test periods (air, oxyfuel) has shown
  - Consistency of model analysis (furnace, bank effectiveness) against plant measurements
  - Impact of ash deposition vs. time on performance
  - Clear differences between air and oxyfuel firing performance (for the two tests analysed)
  - Strong influence of the flame on furnace performance in a single burner facility
    - Difficult to isolate the effect of the flame from the effect of ash deposits
  - However only two test periods considered here; significant further analysis required to establish "rules"
    - More tests at same conditions (repeatability)
    - More tests at different conditions (parametric impact on thermal performance)
- Future testing at CIUDEN's 20MWt es.CO_2 plant will extend the experience to a multi-burner furnace

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Doosan is committed to delivering unique and advanced carbon capture solutions to create a low carbon future.

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Thank you