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A Modelling Appraisal of OxyCoal™ Combustion in Utility Power Plant

British-French Flame Meeting, Lille, France

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Department: Research and Development

OxyCoal-UK Phase 1

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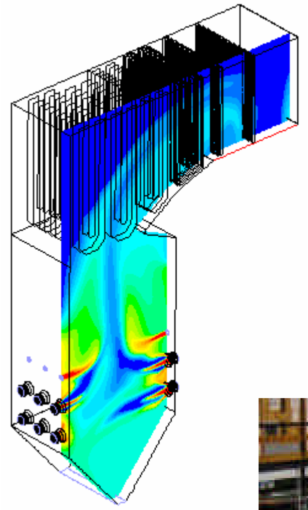
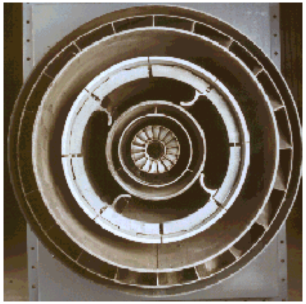
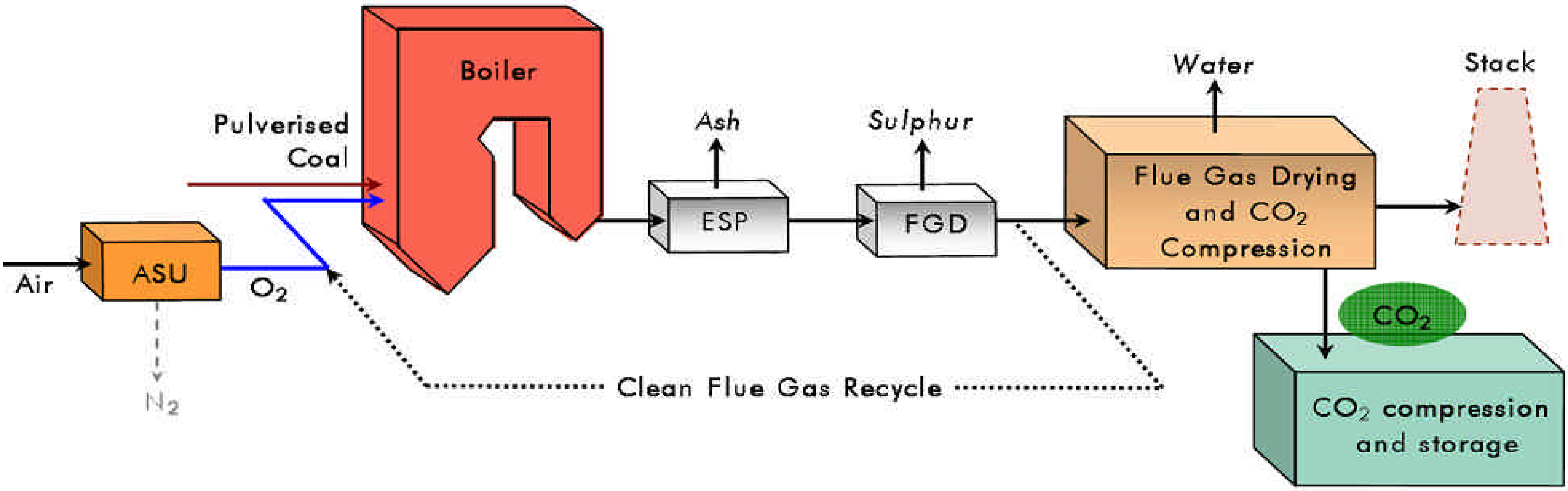




Oxyfuel Technology



- Air Separation Unit (ASU) to supply nearly pure O_2; N_2 is removed from the process prior to combustion to produce a flue gas that is mostly CO_2 and H_2O
- Fuel burned in O_2/CO_2 atmosphere
- Flue Gas Recycle (FGR) mitigates high temperatures from combustion in pure O_2 to maintain combustion and boiler thermal performance
- High CO_2 content allows simple compression cycle for CO_2 purification and capture

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Three Stage Development Programme

To develop a competitive oxyfuel firing technology suitable for full plant application post-2010

- A phased approach to the development and demonstration of oxyfuel technology

- **Phase 1:**
  - Fundamentals and Underpinning Technologies (OxyCoal-UK Phase 1, 2007 to 2009)

- **Phase 2:**
  - Demonstration of an Oxyfuel Combustion System (OxyCoal-UK Phase 2, 2007 to 2009)

- **Phase 3:**
  - OxyCoal™ Reference Designs (2009 to 2010)

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OxyCoal-UK Phase 1

Coal Selection

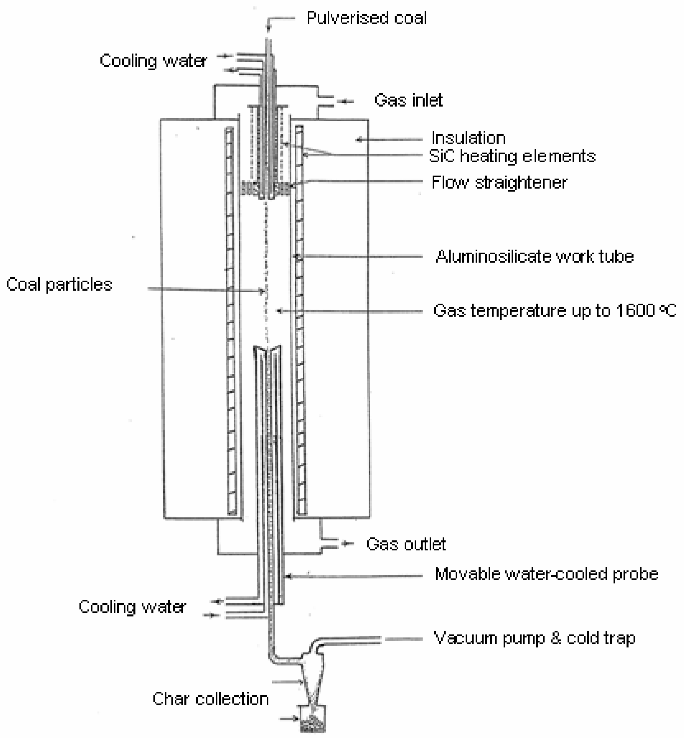
Coal Origin	Colombian	UK 1	South African	Russian	Indonesian	UK 2
Volatile Matter (% wt daf)	40.7	37.2	29.0	38.4	48.6	38.7
Fuel Ratio	1.46	1.69	2.45	1.61	1.06	1.58
Ash (% wt, dry)	9.1	19.3	16.2	13.2	3.2	12.4
S (% wt, daf)	0.68	2.60	0.67	0.37	0.18	1.93

- Representative range of volatile matter, ash, sulphur and geographic origin
- Indigenous and internationally traded coals fired by UK utilities

Drop Tube Furnace

Equipment and Test Programme

- Electrically heated drop tube
  - Gas temperatures up to 1400°C
  - Residence times to 1000 ms
  - Variable gas composition
- Devolatilisation and char burnout behaviour
  - 900, 1100, 1300°C
  - 200, 400, 600 ms
  - N_2 and CO_2-rich atmospheres
- Fine (53-75 µm) and select coarse (106-150 µm) size fractions
- Nitrogen partitioning, Intrinsic reactivity, Carbon content

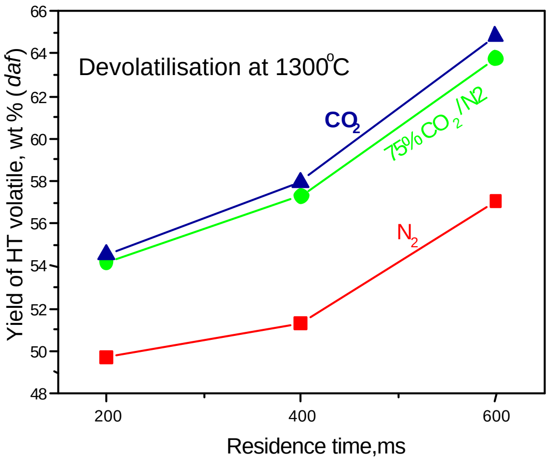


University of Nottingham DTF

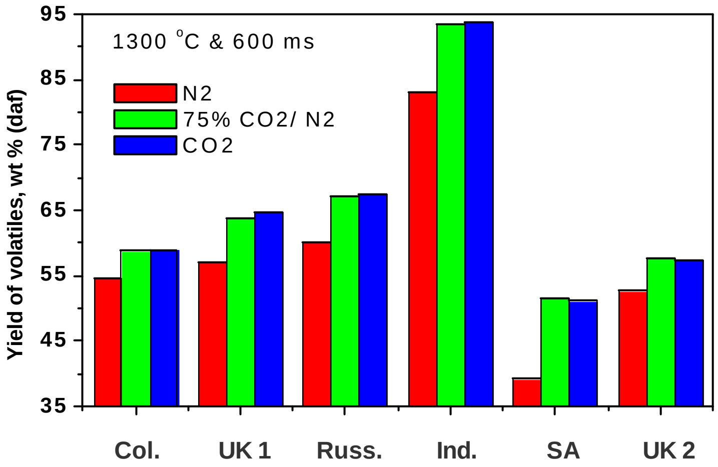
Drop Tube Furnace

High Temperature Volatile Yield

- Volatile yield generally increased with temperature, residence time and CO_2 concentration in oxyfuel atmosphere, indicative of CO_2 gasification



UK 1 Coal Volatile Yield vs Residence Time in Air and Oxyfuel Environments



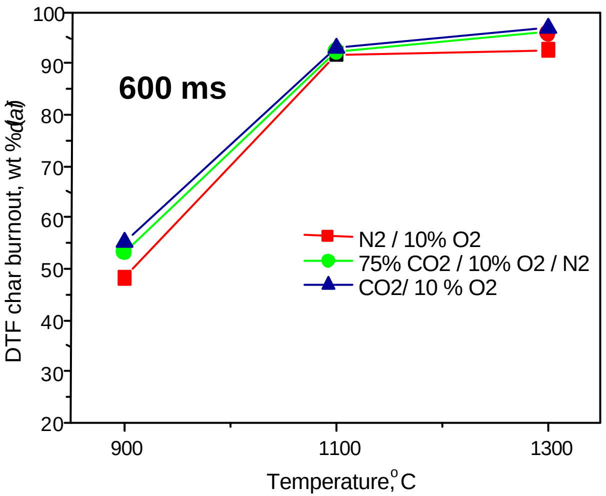
Volatile Yield in Air and Oxyfuel Environments for all coals

- Increased volatile yield corresponds with higher intrinsic reactivity as determined by Thermogravimetric Analysis

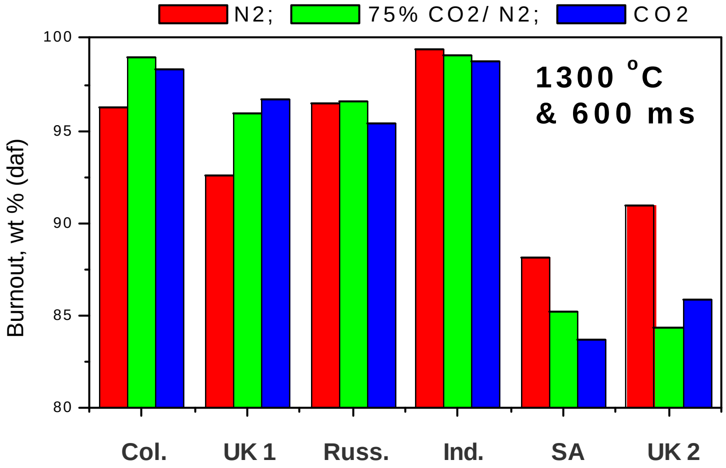
- The proportion of nitrogen in the volatile phase increased under oxyfuel conditions

Drop Tube Furnace

Char Burnout



UK 1 Coal Burnout vs Temperature in Air and Oxyfuel Environments



Burnout in Air and Oxyfuel Environments for all coals

- Char conversion can either be enhanced or suppressed by presence of CO_2
- The amount of carbon in the unburned char for two coals where gasification was enhanced was found to increase, as did the proportion of nitrogen remaining on the char residue
- Char reactivity may be dependent on coal minerals and their transformation in oxyfuel atmospheres

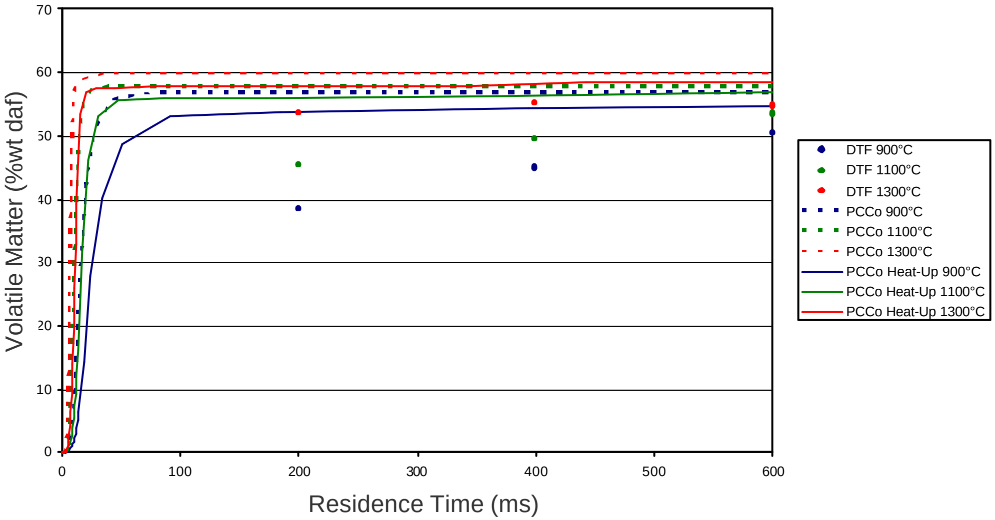
Derivation of CFD Input

Devolatilisation Rate - PC Coal Lab

- DTF residence time too high for rate derivation, therefore coal science program used

- Initial drop tube furnace simulations gave reasonable ultimate yields but apparently poor profiles compared to measurements. Including particle heat-up delay improved the predicted release profiles and ultimate volatile yields

- Flow pattern and coal dispersion within the actual drop tube are likely to contribute to higher variability in yield measurement and true residence time at earlier sampling locations



Drop Tube Predicted Volatile Yield vs Residence Time for Colombian Coal, without and with Particle Heat-up

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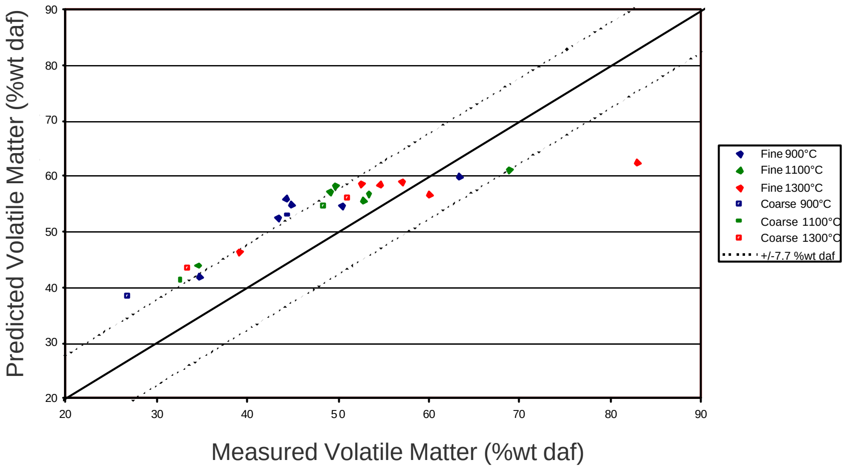
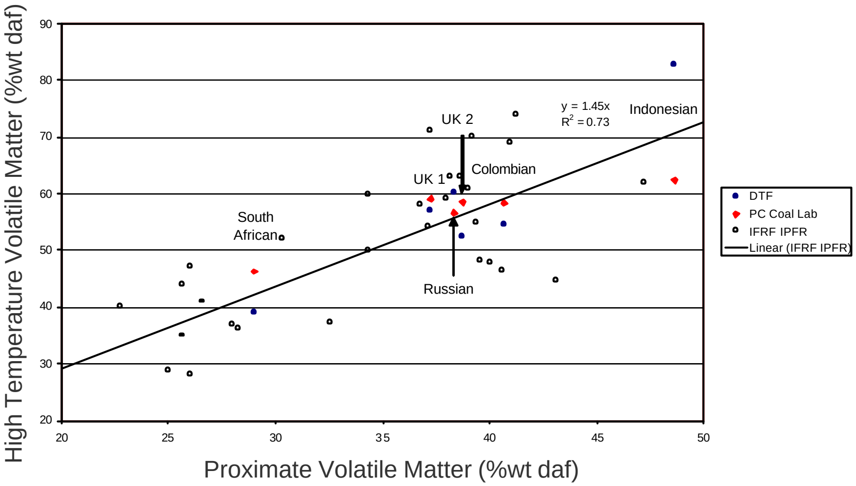
Derivation of CFD Input

Devolatilisation - PC Coal Lab



Predicted vs Measured Drop Tube Volatile Yield (600 ms)



Predicted vs Measured Drop Tube Ultimate Volatile Yield (1300°C) and comparison with IFRF Data (1400°C)

- Prediction of high temperature volatile yield generally within standard error range. Greatest error with very high volatile bituminous

Derivation of CFD Input

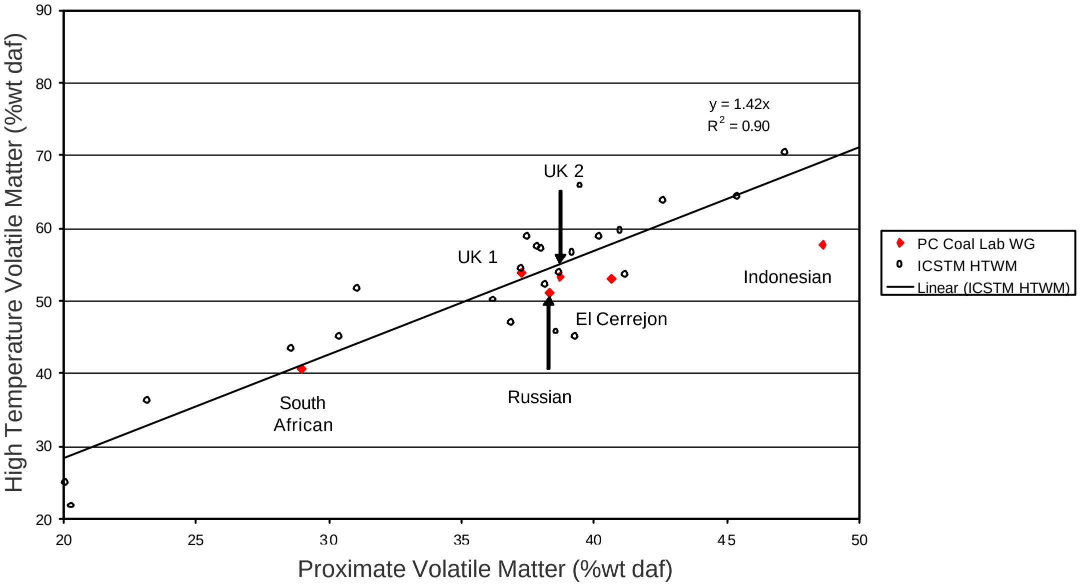
Devolatilisation - PC Coal Lab

- The Wire Grid technique was shown to give similar results and used to generate kinetic parameters for first order devolatilisation rates:

$$-\frac{dm_p}{dt} = k\left[m_p - m_{p,0}\right]$$

$$k = A_o\, e^{-\frac{E}{RT}}$$

- Volatile matter for all coals driven off <30 ms using a nominal heating rate of 70,000 K/s



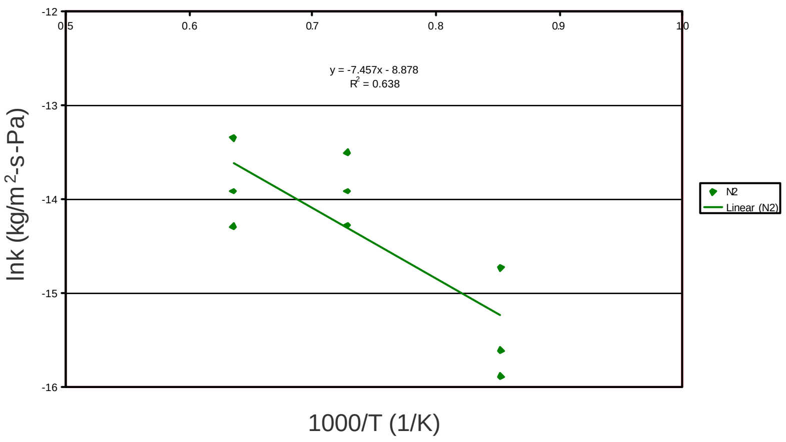
Predicted Wire Grid Volatile Yield vs ICL Data (1600°C)

Derivation of CFD Input

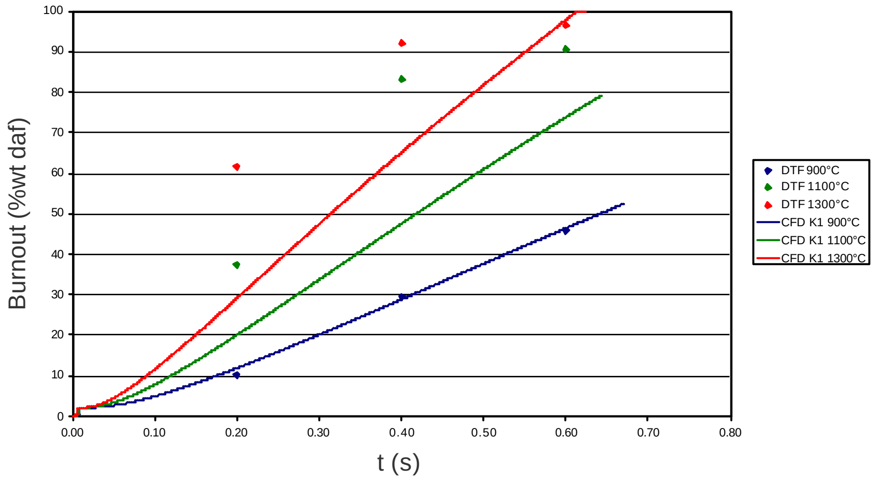
Char Burnout

- Arrhenius plots of measured data for burnout of the six coals in 10% O_2 in N_2 generally gave poor correlations and low apparent activation energies

- A combusting CFD model of the drop tube furnace was used to test original fit parameters and to provide correction to uniform temperature and oxygen concentrations



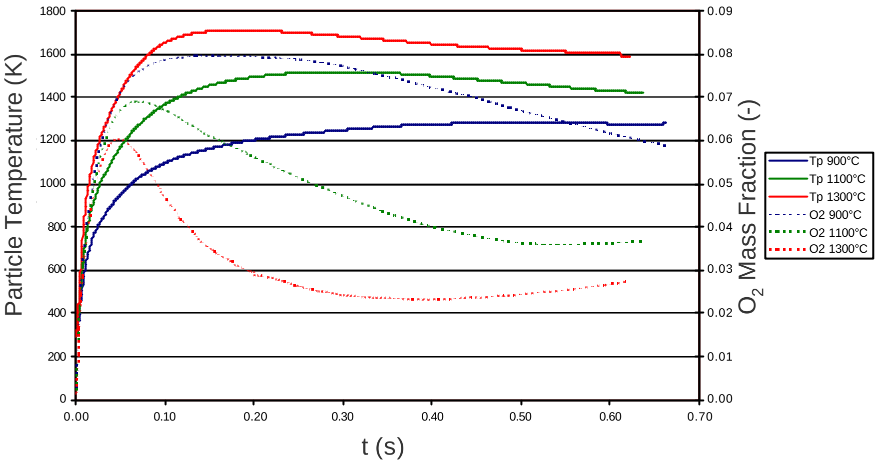
Original First Order Arrhenius Plot (Colombian Coal)



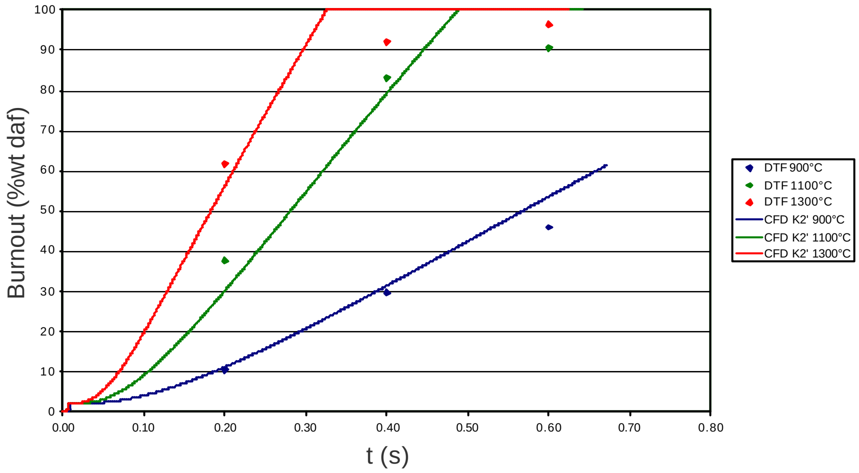
Original Burnout Profiles for Russian Coal

Derivation of CFD Input

Char Burnout



Predicted Typical Laminar Particle Trajectory Temperature and O_2 using Original Fit



Final Burnout Profiles for Russian Coal

- Final profiles, accounting for initial burnout rates and particle histories, gave satisfactory predictions of initial burnout and overprediction of final burnout, as anticipated from first order kinetics for bituminous coals

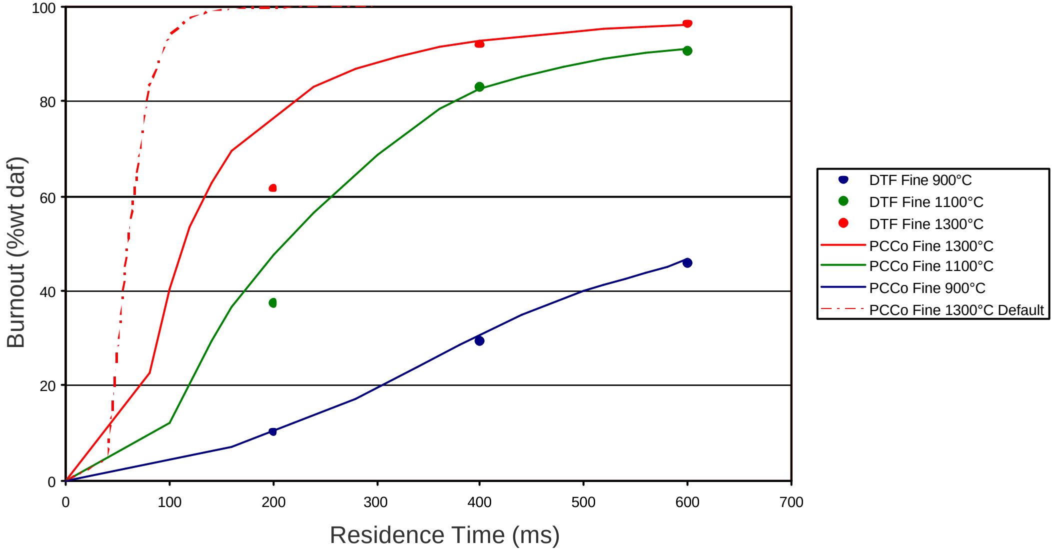
Derivation of CFD Input

Char Burnout - PC Coal Lab

- The Carbon Burnout Kinetics (CBK/E) module of PC Coal Lab was used to predict char burnout in 10% O_2 in N_2 for the six coals using typical profiles of gas temperature and oxygen from CFD burnout models

- Much improved burnout profiles except for all but Indonesian coal. Reactivity parameter adjusted by similar extent for all coals

- PC Coal Lab outputs include a lumped prefix to account for annealing and deactivation plus variable A_o, Ea and order ? how to implement with Fluent?



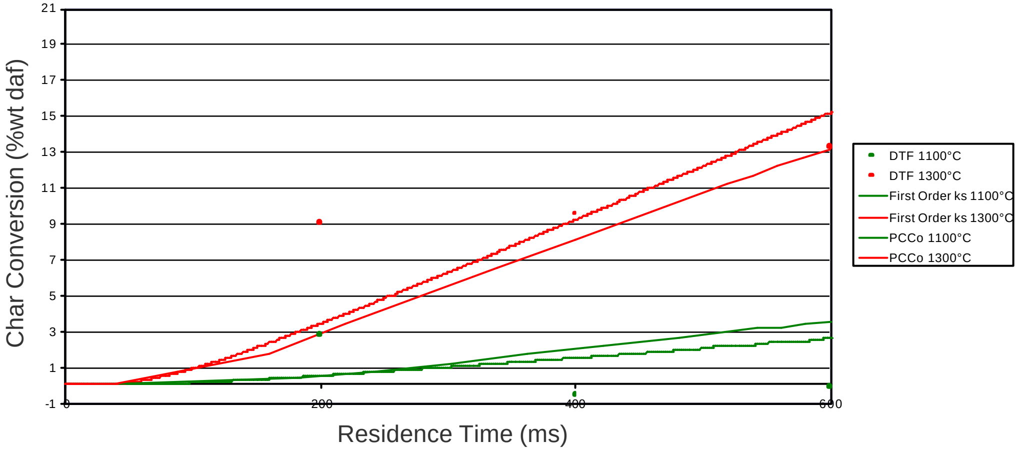
CBK/E Predicted vs Measured Burnout for Russian Coal

Derivation of CFD Input

Char Gasification

- Gasification represents the key difference between air and oxyfuel environments

- However, simultaneous oxidation and gasification, combined with inhibitive effect of oxyfuel environment for some coal chars meant that gasification kinetics could not be derived



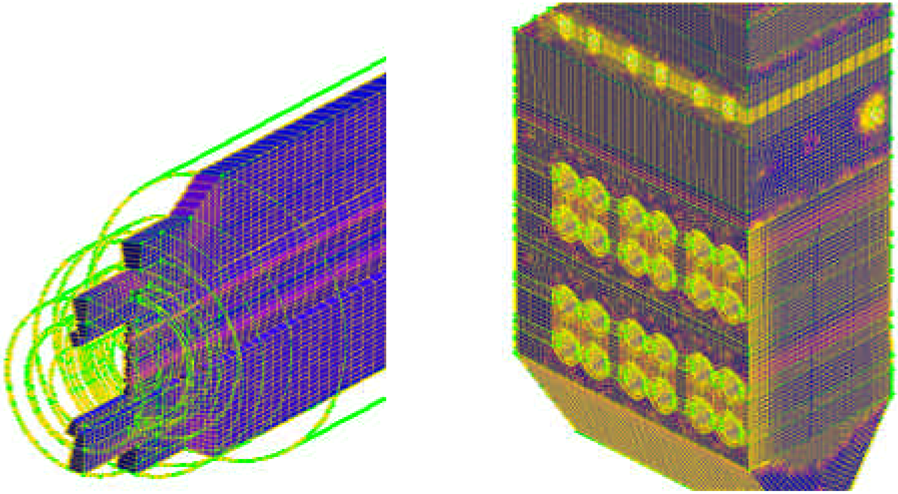
Predicted and Measured Char Conversion vs Residence Time for Colombian Coal Fine Size Fraction

- Assuming that the additional volatile yield during devolatilisation to be attributable to char gasification, similar performance was seen from a first order kinetics fit from literature and PC Coal Lab gasification simulation

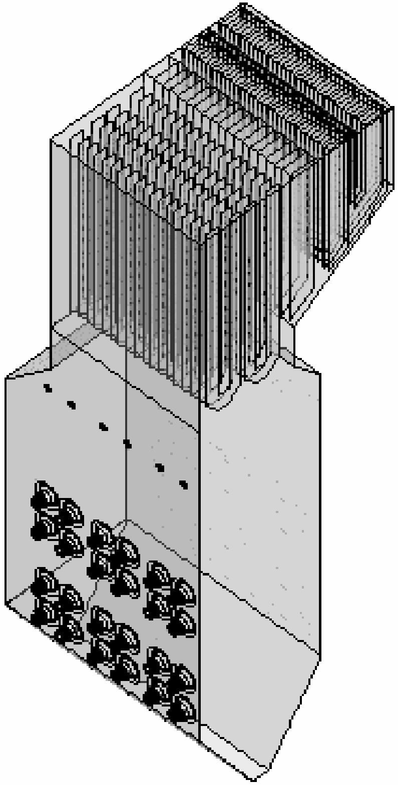
Utility Plant Modelling

Modelled Arrangement

- 500 MWe front wall fired furnace
- Forty-eight 37 MWt burners
- Boosted Overfire Air system



Burner and Furnace Mesh Detail



Furnace Grid Outline

Utility Plant Modelling

Operating Scenarios

- UK bituminous coal, high firing pattern
- Air Firing
  - Low NO_x burners
  - Two stage with Boosted Overfire Air
  - Known boiler performance
- Oxyfuel Firing
  - OxyCoal™ burners
  - Single stage operation
  - Maintain PFGR O_2 and volumetric flow
  - Stoichiometry 1.17
  - Equivalent gas flow
- Uniform coal and air distribution, idle burner in-leakage only

Component (% vol)	Air	Primary FGR	Secondary FGR
O_2	21.0	18.30	30.51
CO_2	-	77.73	55.36
H_2O	-	2.76	13.19
N_2 (plus inerts)	79.0	1.21	0.95

Gas Compositions

Utility Plant Modelling

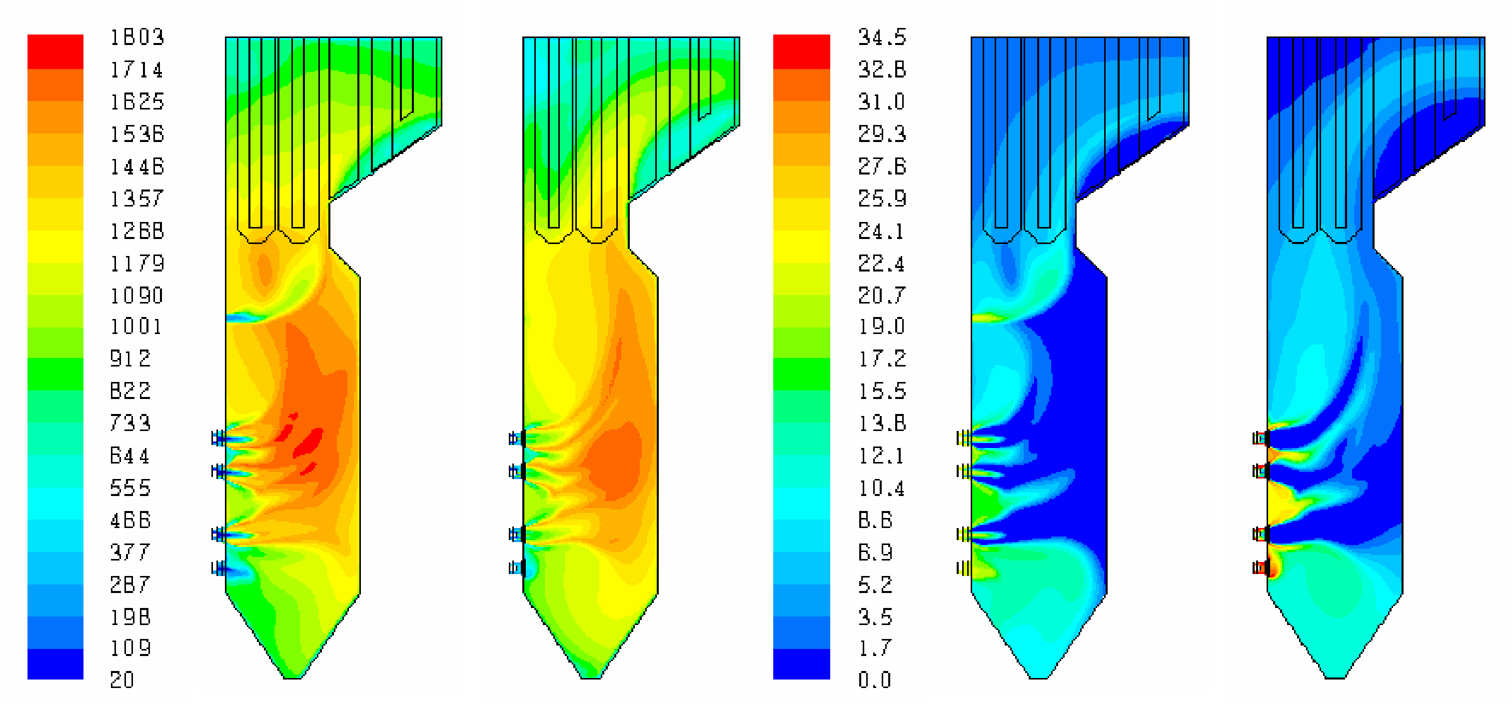
Oxyfuel Modelling Approach

- Gas Phase Chemistry
  - – 2 step reaction of volatiles through CO
- Radiation
  - – Discrete Ordinates model
  - – Absorption coefficient: Exponential Wide Band Model (EWBM[1]) used in place of WSGGM
  - – Particle radiation interaction, ash emissivity adjustment
- Devolatilisation
  - – First order kinetics as derived for air firing
- Char Consumption
  - – Particle Surface Reaction Model
    - $C(s) + ½O_2$? CO [DTF derived]
    - $C(s) + CO_2$? 2CO [Smoot and Pratt]
    - $C(s) + H_2O$? $CO + H_2$ [Smoot and Pratt]

[1] NTUA/ANSYS Inc

Utility Plant Modelling

Combustion Trends



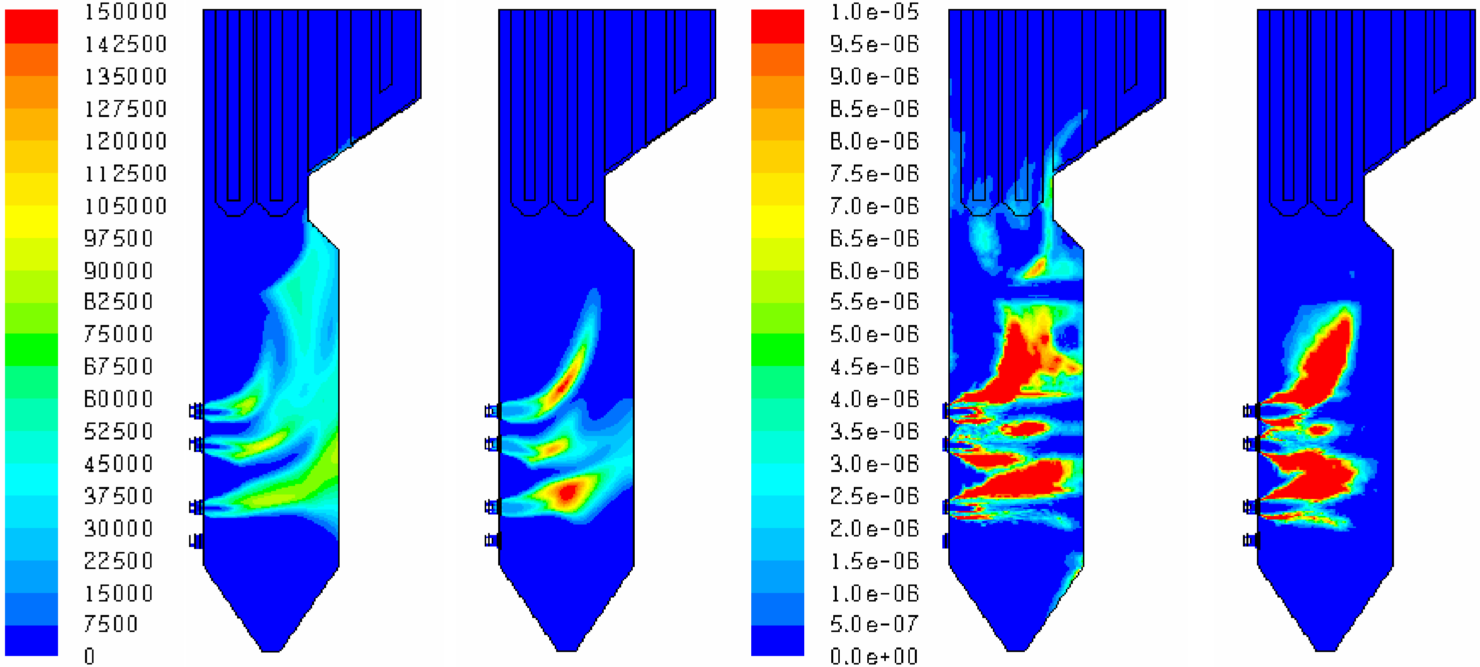
Air Oxyfuel Air Oxyfuel

Temperature (°C) Central Burner Column Oxygen (%v/v dry)

- OxyCoal™ case has reduced gas temperatures, similar flame shape and furnace utilisation

Utility Plant Modelling

Combustion Trends



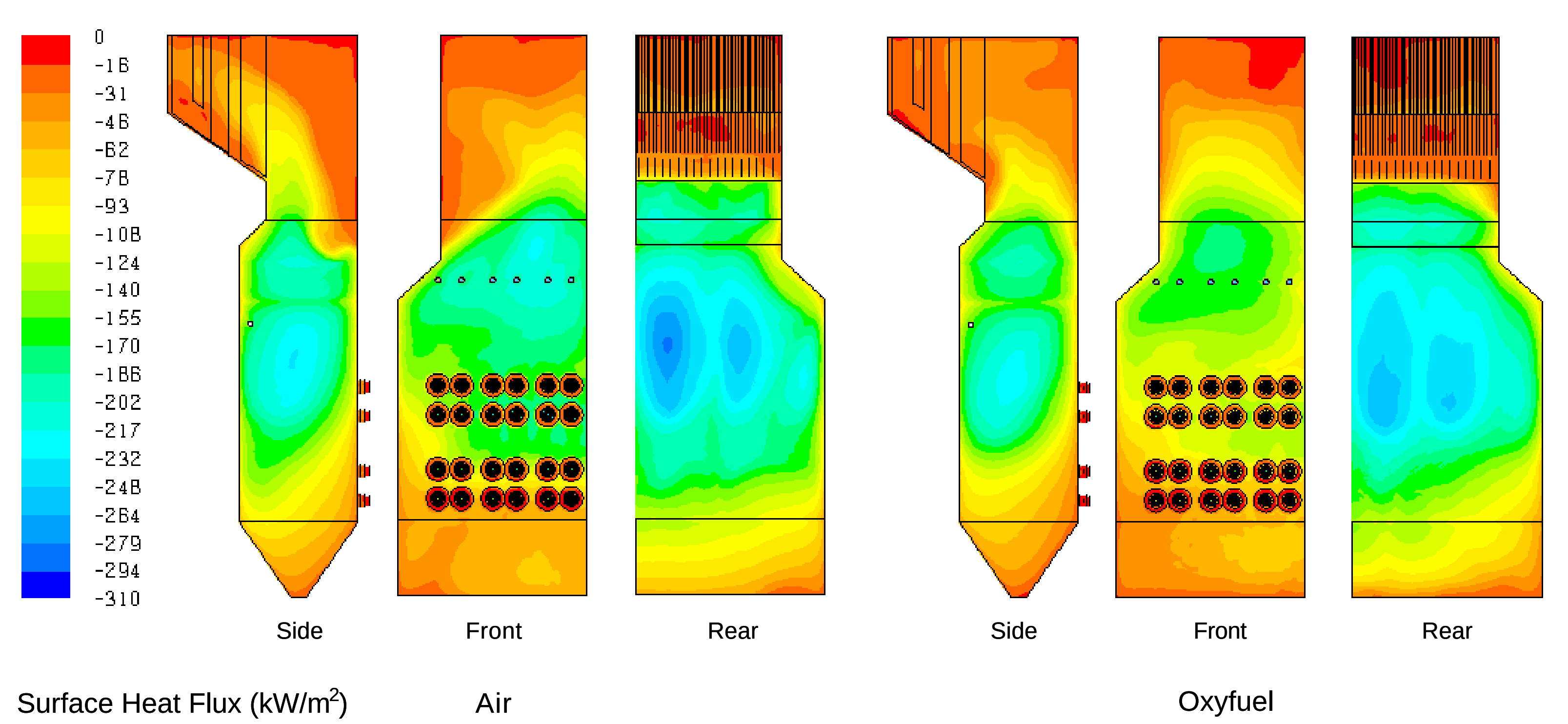
Air Oxyfuel Air Oxyfuel

CO (ppm) Central Burner Column Char burnout (kg/s)

- OxyCoal™ case shows increased peak CO, reduced exit CO and improved burnout

Utility Plant Modelling

Heat Transfer



- Earlier heat release but lower furnace heat transfer under OxyCoal™ operation

Utility Plant Modelling

Heat Transfer

Scenario	Air, Two Stage	OxyCoal™ Single Stage
Arch Temperature (°C)	1418	1423
Furnace Exit Gas Temperature (°C)	1072	1009
Outlet Temperature (°C)	843	819
Total Heat In (MW)	1413.6	1412.4
Heat to Walls (MW)	440.2	411.4
Heat to Pri and Sec Platen SH (MW)	239.0	272.6
Heat to SH Inlet and Outlet (MW)	105.4	105.6
Heat to RH Outlet (MW)	74.2	70.6
Heat in Flue Gas (MW)	532.0	530.0
Unburned Loss (MW)	7.8	0.1
Imbalance (%)	-1.0	-1.7

Design and Predicted Heat Accounts

- Compared to air firing, the OxyCoal™ case gives
  - Similar arch level temperature
  - Reduced FEGT, outlet temperatures
  - Reduced heat absorption by furnace walls (-7% air case)
  - Increased absorption by platen superheater surface (+13% air case)
  - Similar convective pass pick-up
- Radiative heat transfer in oxyfuel case is dominated by reduced flame temperatures in the lower furnace and increased emissivity in upper furnace

Utility Plant Modelling

Emissions

Scenario	Air, Two Stage	OxyCoal™, Single Stage
Oxygen (% v/v dry)	2.98	3.97
CO (ppm @ 6% O_2)	291	74
Unburned Loss (% GCV)	0.6	0
Carbon in Ash (%)	2.0	<0.1
NO_x (ppm @ 6% O_2)	156	155
NO_x (mg/MJ @ 6% O_2)	10.1	7.8

Anticipated and Predicted Emissions

- Lower CO and CIA from OxyCoal firing
- Equivalent NO_x emission on vppm basis, reduced by 23% on mg/MJ basis
  - Negligible thermal source
  - Increased fuel source from specific oxyfuel firing conditions
- Lower than expected baseline NO_x and high burnouts may also relate to assumption of ideal operation
  - Fuel/air distribution
  - Air ingress

OxyCoal-UK Phase 1: DTF Testing and Modelling

Conclusions and Recommendations

- Drop Tube Furnace testing of six bituminous coals has shown:
    - Increased volatile yield and volatile nitrogen under simulated oxyfuel atmospheres
    - Evidence of CO_2 gasification reaction
    - Promotion and inhibition of char conversion in oxyfuel environments

  Gasification by CO_2 and steam should be studied further

- A coal science simulator was found to give satisfactory agreement in prediction of volatile yield against test data and used to generate devolatilisation kinetic parameters

- Supported by CFD modelling, char oxidation data from the Drop Tube Furnace was used to derive basic kinetic parameters for burnout in air. In the absence of suitable data, a CO_2 gasification rate fit from literature was shown to give a reasonable approximation to typical char conversion

- The use of PC Coal Lab for predicting char oxidation and gasification has been investigated and shown to provide reasonable accuracy. Further appraisal for implementation is needed

OxyCoal-UK Phase 1: DTF Testing and Modelling

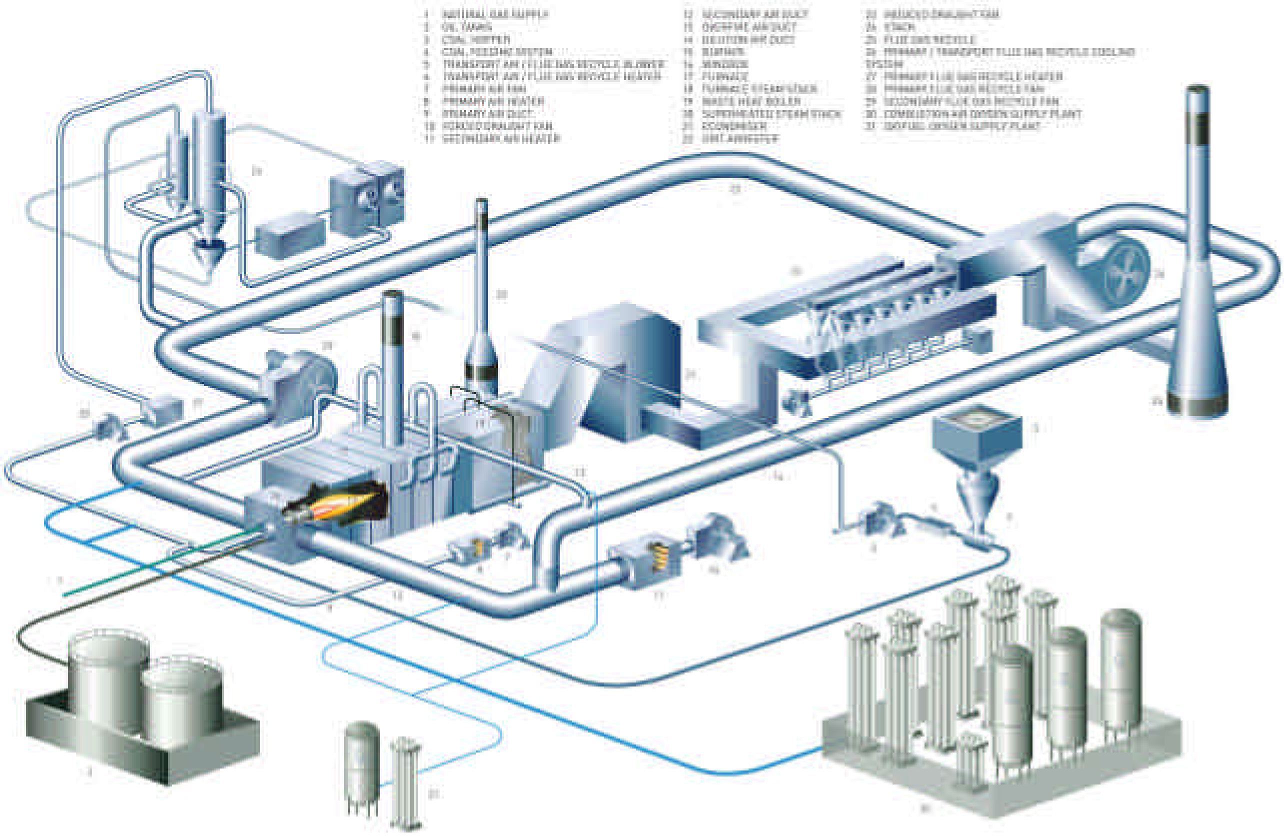
Conclusions and Recommendations

- Modelling of a utility furnace under staged air and unstaged oxyfuel firing conditions suggests that, relative to air firing, the oxyfuel scenario considered may be expected to give:
  - Lower flame temperatures from increased flue gas heat capacity and gas flow rate in burner zone
  - Associated reduction in heat absorption by the lower furnace. Increased platen superheater pick-up due to increased gas absorptivity
  - Acceptable flame characteristics and furnace utilisation using an OxyCoal™ burner design
  - Increased char burnout due to increased oxygen partial pressure and gasification reactions, mitigating reduced temperature
  - Reduced NO_x emission

Further oxyfuel scenario modelling and validation of modelling approach is required

Current Activities

OxyCoal-UK Phase 2: Demonstration of an Oxyfuel Combustion System



Multi-fuel Burner
Test Facility
with Oxyfuel

Current Activities

OxyCoal-UK Phase 2: Demonstration of an Oxyfuel Combustion System

- Establish operational envelope firing UK bituminous coal
  - Heat input, recycle rate, excess oxygen
  - Changeover from air to oxyfuel
- Test Parameters
  - Flame stability, turndown
  - Heat release profile
  - Pollutant emissions
  - Flame visualisation
- Timescale
  - Commissioning - March/April 2009
  - Testing - April 2009

Oxygen Storage Tank

Secondary FGR Fan

Acknowledgements

OxyCoal-UK Phase 1: Combustion Fundamentals and Underpinning Technologies

- Lead Company

  DOOSAN Doosan Babcock Energy

- Industrial Participants

  AIR PRODUCTS
  e·on UK
  RWE
  bp

- University Participants

  Imperial College London
  The University of Nottingham

- Sponsors / Sponsor Participants

  Scottish and Southern Energy
  SCOTTISHPOWER
  EDF ENERGY
  Drax Power Limited
  DONG energy
  VATTENFALL

- Government Support

  Technology Strategy Board
  Driving Innovation
  EPSRC Engineering and Physical Sciences Research Council

Acknowledgements

OxyCoal-UK Phase 2: Demonstration of an Oxyfuel Combustion System

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