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REPORT

INTERNSHIP PROGRAMME ON

CLEAN COAL TECHNOLOGY (CCT) AND CARBON CAPTURE AND STORAGE (CCS) IN UK

5th November to 18th November, 2012

Project on
Developing a Cluster for Clean Coal Technologies (CCT) and Carbon Capture and Storage (CCS) Technologies for the Indian Thermal Power Sector

REPORT
INTERNSHIP PROGRAMME ON
CLEAN COAL TECHNOLOGY (CCT) AND CARBON CAPTURE AND STORAGE (CCS) IN UK

1. **Country Visited:** United Kingdom (UK)
2. **Period of Visit:** 5th November to 18th November, 2012
3. **Purpose of the Visit:** Internship programme on clean coal technology (CCT) and carbon capture and storage (CCS)
4. **Institutions Visited:**
   - Imperial College, London
   - Edinburgh University
   - University of Newcastle
   - University of Leeds and PACT facilities, Sheffield
   - The University of Nottingham
5. **Internship Team:** Three Senior professionals for BHEL

6. **Summary of Learnings :**

- The internship tour was very informative with regard to carbon capture processes from different sources such as power plants, refineries, chemical industries, etc.
- Enhanced the understanding and knowledge on CO_2 transportation, involved risks and pipe line specifications for CO_2 transportation.
- Good understanding of operational problems of oxy-fuel combustion technology
- Great opportunity to interact with many academic experts and visited their facilities for gaining knowledge on newer technologies.
- Established contact with international experts working in the CCS areas
- Able to understand the seriousness of UK government in implementation of CCS in large scale commercial power plants.
- Knowledge on current situation on CCT and CCS projects in UK

7. **Visit to the State of the art institutions working in CCT and CCS domain in UK :**

On 5th November 2012 the visiting team reached London.

1. Imperial College London:

On 6th November, 2012 the team visited the Post-combustion CCS experimental test facility of 1.2ton CO_2/day capacity at Centre for process systems engineering group, Chemical Engineering Laboratory, Imperial College.

Summary: The Internship team visited Imperial College, one of the premier institutions in UK on 6th November, 2012. During their visit, the team had series of elaborate interactions with experts in CCS such as: Dr. Paul Fennell, Senior Lecturer, Chemical Engineering Department on the CO_2 removal process using carbonate (Chemical Looping Combustion), biomass pyrolysis and oxy-fuel combustion, Dr. Niall Mac Dowell, Research Associate, Energy Molecular Systems Engineering on molecular modelling and thermodynamic modelling in post-combustion process simulations and Dr. Collin Hale, Senior Teaching Fellow, Imperial College, London on operation and techniques used in capturing CO_2 from the flue gas using solvent absorption.

Post-combustion CCS Experimental Test Facility:

The Carbon Capture Pilot Plant uses over 250 instruments, measuring parameters including temperature, pressure, flow rate, pH, level and gas composition. It consists of two primary columns (absorber and stripper), both 11 metres high and a 0.5 metre in diameter and fitted with visualisation ports, allowing the processes inside to be observed by students and researchers. The absorber column runs at 1.8 barg, and fluids can be re-circulated at a rate of 1200kg/hour. The Plant is capable of capturing 1.2 tonnes of CO_2 per day. Total investment on pilot scale carbon capture plant was of £2 million with 50% contribution from ABB. The agreement between ABB and Imperial College gives the university access to the most advanced control and instrumentation technology available from any manufacturer, as well as life cycle services and support for the installation.

In return, ABB has access to the carbon capture pilot plant for its own use and uses the facility for customer demonstrations and training, staff learning such as inter-divisional training and hands on experience for its apprentices and graduate engineers. ABB conducts experiments in new technology in a low risk, well-managed environment to gather Beta site test data. The overall pilot scale plant is shown in Figure 1.

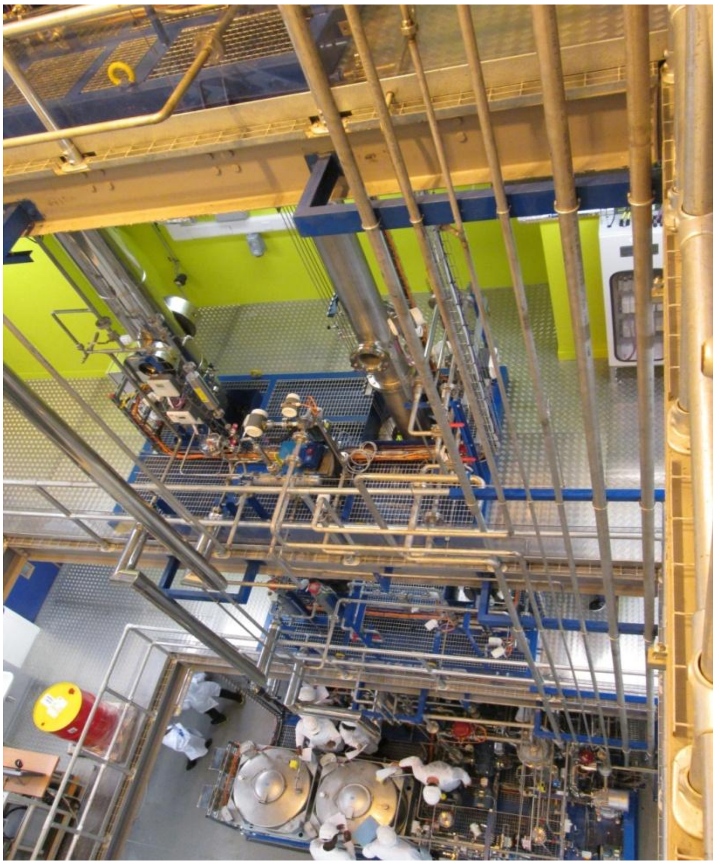


Figure 1: Overall picture showing the CO_2 capture pilot plant

Working Procedure of CO_2 Capture Pilot Plant:

Step 1: Carbon dioxide (CO_2) and nitrogen enter the system. The gas mixture is passed into a saturation vessel, so that the CO_2 becomes saturated with water before passing into the absorber tower. This helps with the subsequent CO_2 absorption process.

Step 2: The gas rises up the absorber tower as the mono-ethanol amine (MEA) solution flows down from the top. The CO_2 absorption process requires specific pressure, temperature and pH conditions. Live interactive schematic diagram of absorption column is shown in Figure 2.

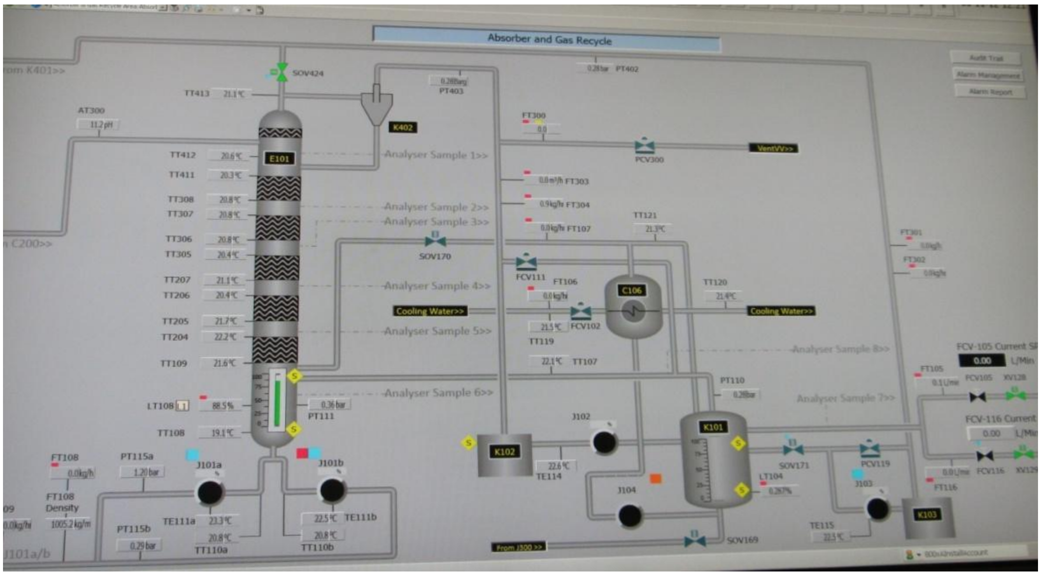


Figure 2: Schematic representation of absorber and gas recycle.

Step 3: The CO_2-rich amine solution is pumped to the top of the regenerator tower. It then flows into the re-boiler by natural convection processes, where the liquid is heated and a fraction turns into vapour. Live interactive schematic diagram of stripper column and reboiler is shown in Figure 3.

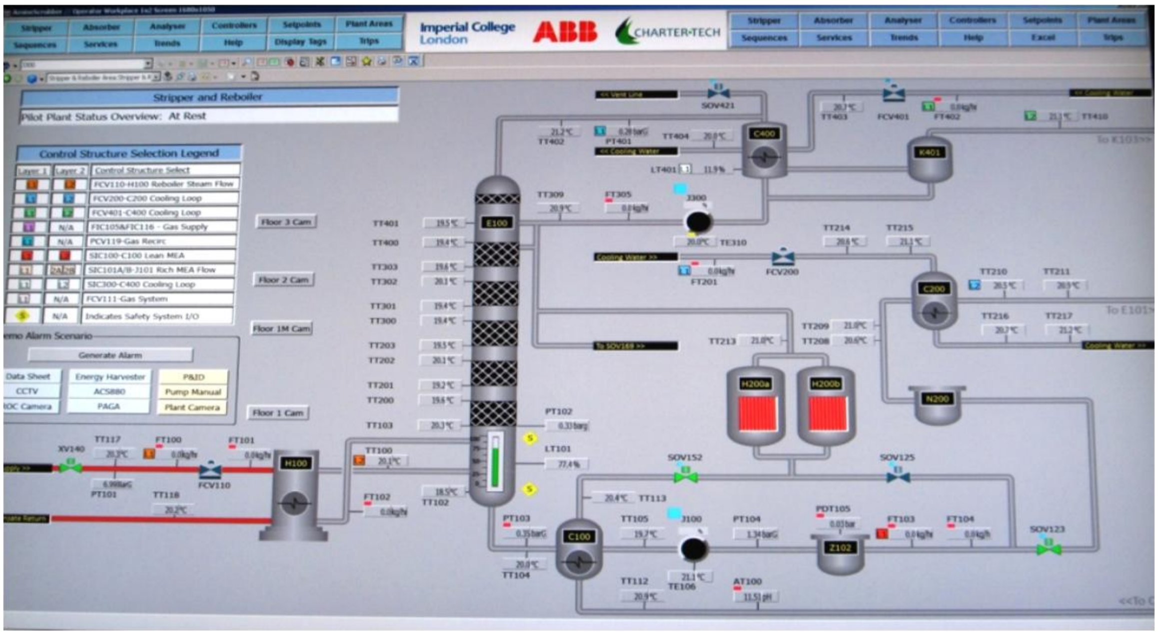


Figure 3: Schematic representation of stripper and reboiler.

Step 4: The vapour passes up the regenerator tower into the condenser where the amine solution condenses, leaving the CO_2 as a gas to be collected. The CO_2-free liquid MEA returns to the regenerator and is then pumped back to the top of the absorber tower.

2. Edinburgh University

On 7th and 8th November, 2012, at the Edinburgh University, the team was able to attend a workshop on 'CCS in Industries'.

Summary: The team was able to interact with the prominent speakers from reputed industries and universities of UK such as University of Newcastle, Progressive Energy, DECC, BIS, Johnson Matthey, Grow How, Air Liquide, TOTAL, University of Edinburgh, Ineos, UKCCSRC, NEPIC, BOC-Linde, National Grid, Scottish Carbon Capture and Storage (SCCS) and Imperial College London.

The participation in the workshop has been very useful for the Indian internship team as it provided in-depth knowledge on many new technology developments and trends in the carbon capture and storage integration in various industrial sectors such as refineries, chemicals manufactures, bio-methanol, etc.

From the discussions it was clear that by 2018 or 2019, UK is going have their first large scale commercial CO_2 capture and storage system. Presently, UK government had called for a contest to put up a large power plant with CCS. As a response to this call, 12 bidders from various organizations had participated. Out of all 4 projects have been shortlisted. The amount of money UK Govt. wanted to invest and number projects that would be approve is yet to be known. The four short listed projects is given below

- Peterhead gas project - 340 MWe - Post-Combustion CCS
- Captain clean energy project - 570 MWe - IGCC
- White Rose project - 304 MWe - Oxy-fuel capture plant
- Teeside low carbon project - 330 MWe - Pre-combustion (IGCC) CCS - Gas fired plant.

Department of Energy on Climate Change (DECC) will be announcing the competition results during the month of December 2012 regarding who will be awarded the contract. Right now UK is not permitting any power plant which emits more than 450 grams of CO_2/kWh. In other words, no permit is provided for coal fired power plants as of now, only gas fired plans are given permission. The recent built/building power plants must be 'CO_2 capture ready' for future installation in terms of design and space.

Picture: Workshop on industry CCS at Edinburgh University

On 8th February, 2012, the internship team participated in the CCS workshop which provided the team knowledge on a package of global CCS initiatives successfully being implemented currently. Some of the very interesting presentations and discussions covered were on the topics as below:

1. **Presentation on *"Development of Carbon Capture and Storage in China"* by Dr. Xi Liang:**

Summary: Dr. Xi Liang, presented power plant scenario and CCS works in China. He shared that an estimated 1,062 GW of new capacity will be installed in China from 2010 to 2030, resulting in a total installed capacity of 1,936 GW—equivalent to the current installed capacity of the United States and European Union combined. Hence, after energy efficiency and fuel switching, CCS will likely be China's primary option for reducing carbon emissions in the power, chemical and other industrial sectors that is depended on fossil fuels. He also shared that in China 37% of power plants out of 260 can be retrofitted and 53% cannot be retrofitted and 10% plants cannot be classified. China is currently evaluating 9 projects for CCS work on commercial scale and two plants have carried out demonstration of CCS.

Some of the Large CCS Projects Identified in China during 2011 includes:

• **Daqing Carbon Dioxide Capture and Storage Project** – a super-critical coal fired power plant that would capture around 1 Mtpa of CO_2 through oxyfuel combustion, developed by the China Datang Group in partnership with Alstom.

• **Dongying Carbon Dioxide Capture and Storage Project** – a new build coal fired power generation plant with a planned capture capacity of 1 Mtpa of CO_2, also developed by the China Datang Group.

• **Shanxi International Energy Group CCUS Project** – a new, super-critical coal-fired power plant with oxyfuel combustion being developed in partnership with Air Products, with a capture capacity of more than 2 Mtpa of CO_2.

• **Jilin Oil Field EOR Project (Phase 2)** – EOR operations at the Jilin oil field, where around 200,000 tpa of CO_2 from a natural gas processing plant are currently being injected, are scheduled to be expanded to more than 800,000 tpa from 2015.

• **Shen Hua Ningxia Coal to Liquid Plant Project** – a new build coal-to-liquids (CTL) facility developed would capture around 2 Mtpa of CO_2, it is one of three LSIPs (Large Scale Integrated Projects) developed by the Shenhua Group.

2. Presentation on "*Retrofitting existing Power Stations with Post-combustion CO2 capture*" by Dr. Mathieu Lucquiaud

The next lecture was on retrofitting existing power plants with post combustion capture by Dr. Matheui. He spoke about different strategies that capture ready power plant can adopt with respect to steam utilization from IP & LP turbine. As much as 50% of the low pressure steam is used to heat the CO_2 rich amine solution to strip CO_2 from the amine solution in a stripper, contributing to efficiency penalty as high as 10-12%

The efficiency penalty is defined as follows:

Efficiency penalty (% point) = Fuel specific emission x Electricity output penalty

$$= \frac{\text{kg CO2}}{\text{MW}} \text{ x } \frac{\text{kW}}{\text{ton CO2}}$$

The lecture also mentioned that the space required for Carbon Capture Readiness is almost 50-100% of space occupied by Power Plant without CCS.

3. Presentation on "*Current position of CCS in UK*" by Dr. Philippa Parmiter

During the lecture, Dr. Philippa Parmiter described about different projects that are currently explored by the UK Government for CO_2 capture on commercial scale. It was told that UK government is planning to invest £1 billion (yet to be finalized) on different CCS projects, starting from early next year. Some of the major research projects by SCCS include:

- Calculating the CO_2 sequestered by mineral trapping
- Seal evaluation and mineral reactions to measure mud rock performance over geological timescales
- Assessing CO_2 retention and leakage up fault seal
- Consultancy for site-specific evaluation of CO_2 storage around the UK

4. Presentation on "Next generation carbon capture" by Dr. Maria-Chiara Ferrari

Dr. Ferrari represented the Next generation Carbon capture group of University of Edinburgh. She is currently working on "Innovative Gas Separations for Carbon Capture (with St Andrews, Cardiff, Imperial College, Manchester and University College London)". The aim of the project is to

- Investigate all gas separation options for carbon capture: absorption, adsorption, and membranes.
- Apply a range of experimental and molecular modelling techniques to determine equilibrium and kinetic properties of nanoporous materials, which are being developed for CO_2 capture.

- Develop detailed simulations of membrane and adsorption units that will be used for parameter estimation and process optimization in the integration of carbon capture in power plants.

Materials Tested and Experimental Results:

The materials that are tested for CO_2 Adsorptivity studies includes

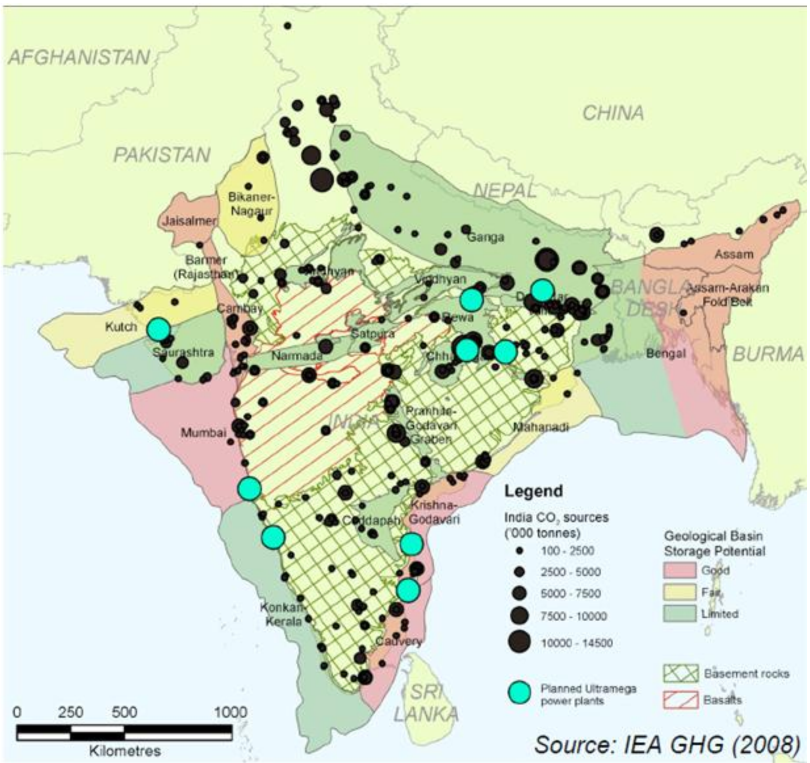
- **Polymers of Intrinsic Microporosity (PIM)** (done by University of Manchester and Cardiff University),
- **BPL Carbon -** Carbons with different surface functional groups e.g. BPL-Piperazine, BPL-Crown ether, BPL-Benzeneacetamide (done by University of Manchester, Cardiff University, University College London (UCL)),
- **Oxides** (UCL) and
- **Metal-Organic Frameworks (MOFs), Zeolites & Mesoporous Silicas** (done by St. Andrews University).

During the lecture Dr. Ferrari spoke about ceramic membranes and adsorbents to separate CO_2 from the flue gas and natural gas, etc. We have visited their laboratory facilities and seen the adsorber and stripper columns and online infra red (IR) based CO_2 analyzer, which is used to monitor the CO_2 concentration in flue gas line. This will help in calculating adsorbent efficiency.

5. Presentation on "*CCS Technology Transfer as part of a Low-Carbon Development Strategy for India*" by Rudra V. Kapila

Ms. Rudra Kapila presented on the CCS technology transfer as part of a low-carbon development strategy for India, where she spoke about different strategies for India to carry out CCS. For example exchanging LPG/LNG with CO_2 for enhanced oil recovery (EOR) with Middle East. Figure 4 shows the potential geological storage site in India for CO_2 storage. The figure also indicates the capacity of the storage site and as well as its ready implementability. From this study it can be seen that most of the identified good CO_2 storage sites located near the coastal line, which already has some oil reserves in it.

Figure 4: CO_2 geological storage potential in India.



3. Scottish Government Office, Glasgow:

The Indian team visited the Scottish Government Office, Glasgow on 9th November, 2012

Summary: . The team made a presentation on the various CCT and CCS initiatives undertaken by BHEL and also on the EU supported Cluster project. The Scottish Government Office representative, Dr. Collin Imrie from the Directorate of Energy and Climate Change has explained their mode of operation and strategies to set up the roadmap to make the CCS as their mainstay for future energy supply.

Scottish Government has kept their target to limit their CO_2 emissions less than 50 g/kWh by 2020 from thermal power plants. This clearly shows that UK is very keen in investing on "permanent" CCS. As mentioned earlier, department of climate change (DECC) is currently short listing different CCS projects to invest about £1 billion. It was also mentioned that there are projects which monitors CO_2 release approximately below 200m in the sea to find out the effect of CO_2 release on eco-systems. From preliminary results, it was told that there was only minimal effect of CO_2 release on ecological system.

4. M/s Howden Global, Renfrew

During the same day, the team has also met representative from Howden Global in Renfrew, a company which designs and manufactures Air pre-heaters (APH), fans, compressors, blowers, DeNOx, FGD and BOFA. The team interacted with Mr. James Nimmo, Mr. Dougal Hogg and Mr. Ken Robinson from the company.

Howden in collaboration with INVENTYS have developed a new technology called inventy's VELOXOTHERM™ for post-combustion CO_2 capture from power plant. It is a separation process implemented in a rotary adsorption machine (RAM). As the RAM rotates, sorbent arrays pass in and out of the process streams, separating CO_2 from the flue gas in a temperature swing adsorption (TSA) process. Howden in collaboration with Doosan, inventys, BP, Shell is going to put up a 5MW plant in Canada with RAM. Schematic representation of total power plant with CO_2 capture is shown in Figure 5. Figure 6 shows the rotating adsorption machine (RAM) for CO_2 capture from flue gas.

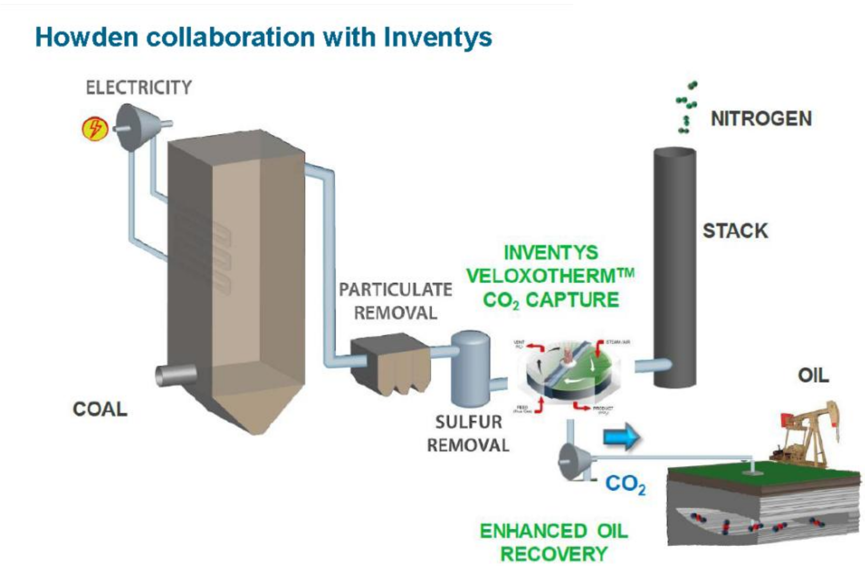


Figure 5: Schematic lay-out of post-combustion CO_2 capture from power plant.

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Figure 6: Rotating adsorption and desorption experimental set-up for post combustion CO_2 capture.

5. Newcastle University:

Summary: On 12th November, 2012, the Indian Internship team interacted with Dr. Julia Race, Pipeline Engineering specialist in the School of Marine Science and Technology at Newcastle University. The interaction focused on several factors of transportation of CO2 in pipelines to the storage site.

Dr. Julia Race presented a completely different aspect of carbon capture and storage i.e., transportation of CO_2 using pipelines to storage site. Their group is currently working on project called MATTRAN, which deals with materials for the next generation of CO_2 transport systems. This is a multi-partner, consortium project co-ordinated by the school of marine science and technology at Newcastle University and co-sponsored by the Engineering and Physical Sciences Research (EPSRC) and E.ON. MATTRAN brings together a team of scientists, mathematicians and engineers working from Newcastle University, Cranfield University, The University of Edinburgh, Imperial College of London, University College London and the University of Nottingham. The team is working from the molecular scale of the CO_2 in the pipeline to the macro scale of fracture propagation and pipeline failure to produce the required data in a systematic and co-ordinated manner.

The large scale implementation of CCS cannot be realised without a pipeline network that is economic, safe and efficient. Most of these studies are theoretical studies using mathematical software. Experiments for corrosion studies and some rupture experiments to validate their modelling studies were carried out.

Major thrust in MATTRAN is review of CO_2 specification for pipeline transportation, effect of impurities on pipeline design, CO_2 specification for fracture control, specification to prevent material degradation, and to prevent cracking.

The focus for CCS projects is to capture CO_2 predominantly from power plants. The amount and type of impurities in the CO_2 stream captured from a power plant are dependent on the capture process, the capture technology, the fuel source, regulatory constraints and economic considerations. Another challenge for a pipeline specification is illustrated by the difference in the levels of some impurities between different technologies; for example, in post combustion capture the combined levels of Ar and N_2 could be as low as 0.01 vol%, while for some types of oxy fuel capture technology, the combined levels could be over 10 vol%. The presence of different impurities such as H_2O, SOx, NOx, H_2S, H_2, Ar, CH_4, etc. and their effect on CO_2 line is given in Table 1. This range of requirements for a pipeline specification makes it difficult to specify the CO_2 composition from the point of view of the capture processes and the components that could be present in the captured CO_2 stream.

Table 1: Presence of different impurities and its effects on CO_2 pipeline

	Corrosion	Cracking	Hydrate formation	Health and safety
H_2O		Promotes cracking	Promotes hydrate formation	
SO_x	Promotes corrosion	Effect unknown		
NO_x			Effect unknown	Toxic in event of release
H_2S	Effect unknown			
CO		Promotes cracking		
H_2		Effect unknown	Promotes hydrate formation	
Ar	Not studied		Effect unknown	
N_2			Promotes hydrate formation	Effect unknown
O_2	Promotes corrosion	Not studied		
CH_4	Not studied		Effect unknown	

In pipelines it is most efficient and economical to transport the CO_2 as a supercritical or dense phase fluid, as under these conditions, the fluid has the density of a liquid but viscosity of gas. The phase diagram for CO_2 gas is shown in Figure 7.

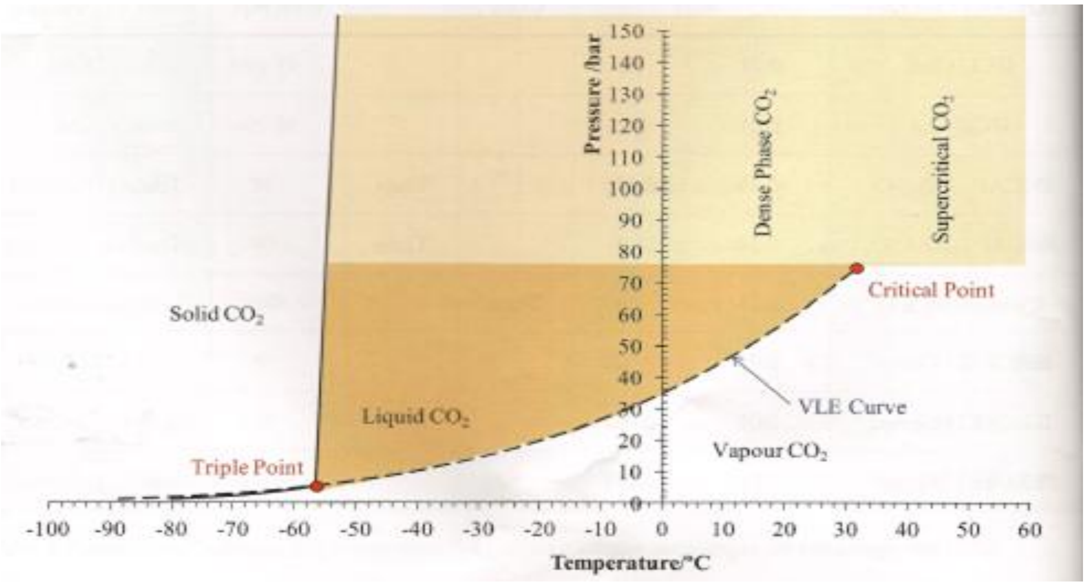


Figure 7: CO_2 phase change diagram

The phase behaviour of CO_2 changes when impurities are introduced into the system. It depends on type, amount, and combination of impurities present, as the impurities interact with both CO_2 and among themselves. The general effect of impurities when added into the CO_2 stream is to raise the critical pressure and open out a two phase area in the phase diagram. The effect of impurities on CO_2 compression pressure is shown in Figure 8.

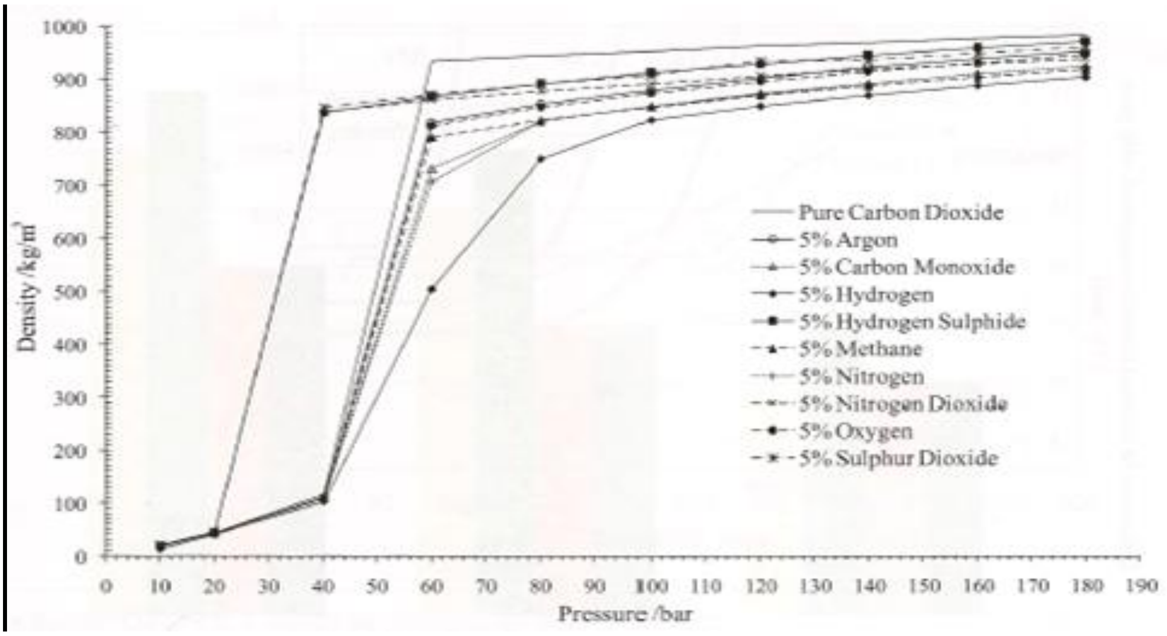
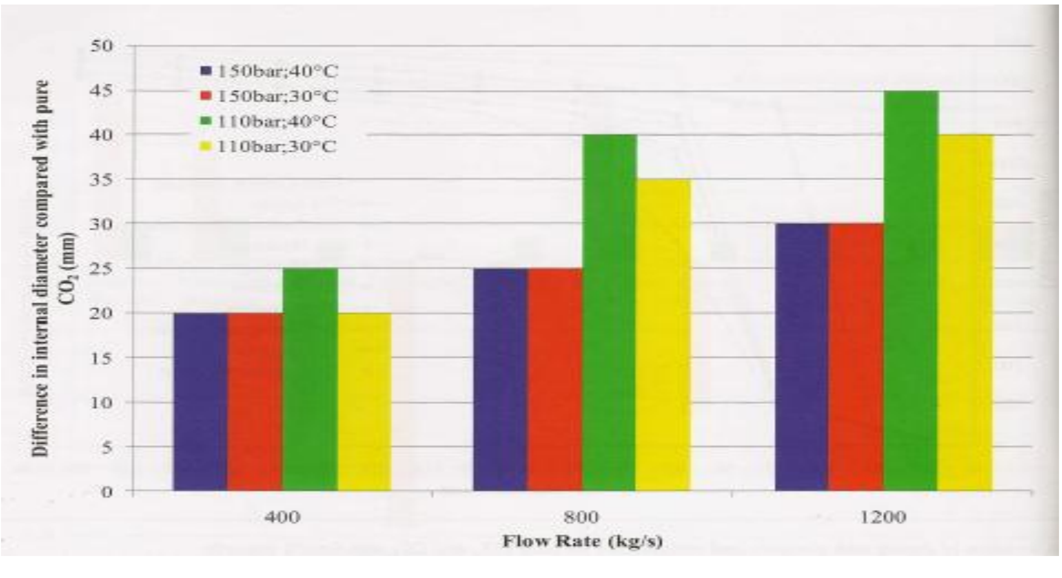


Figure 8: Effect of impurities on CO_2 compression pressure.

Other important platform of study is fracture control. The problem of ductile fracture propagation will lead to fluid decompression and a decompression wave propagates in both directions from the fracture point at a velocity which is dependent on the fluid properties. Whether the fracture will propagate once initiated is dependent on whether there is sufficient driving force for proportion, whether the initial pressure is high enough to sustain a fracture. If fracture can be sustained, then a crack will propagate along the pipeline at a velocity which is dependent on the strength and toughness of the pipe steel and also on the geometry of the pipeline.

In order to illustrate the effect of the specification of the pressure, temperature and the level of impurities on pipeline diameter, a series of hydraulic simulations were done. The study was conducted for a pipeline length of 100 km with 0.0002 bar/m pressure drop along the route; the ground temperature was specified as 5^0C and the results are presented in Figure 9. The effect of impurities on CO_2 stream on pipeline design, operation, integrity, health and safety has been considered in this project.

Figure 9: Effect of impurities on CO_2 transportation at different pressures and temperatures



6. University of Leeds:

On 14th November, 2012, the team visited 250 kw vertically down fired oxy-fuel combustion experimental facility, 20 kw down fired combustion chamber and Post-combustion CO_2 capture using amine solution at the Pilot Scale Advanced Capture Technology (PACT) facilities.

Summary: At the university two seminar sessions were organized by two specialists, Dr. Alessandro Pranzitelli and Dr. Richard Porter. The sessions were very informative and the team was able understand the various CCT and CCS works that are being carried out by Energy Technologies Innovation Initiatives (ETII) group.

First Presentation by Dr. Richard Porter was on carbon capture process technology using amine solution, process modelling studies and techno-economic assessment for different combustion technologies with CCS. During carbon capture simulations in absorber, oxidative, thermal and atmospheric degradation of amine solution were considered. Complex formation of amine solution by reacting with NOx were included. It was claimed that these studies help in understanding the effect of O_2 concentration in flue gas for oxidative degradation in presence of metal ions such as Fe^{3+}, Cu^{+} and Fe^{+} and effect of temperature on thermal amine degradation, etc.

Using techno-economic analysis the cost of electricity (CoE) of various combustion technologies with carbon capture and storage was evaluated to understand possible energy penalty in each technology. Cost of Electricity for each of the technology is given in Figure 10.

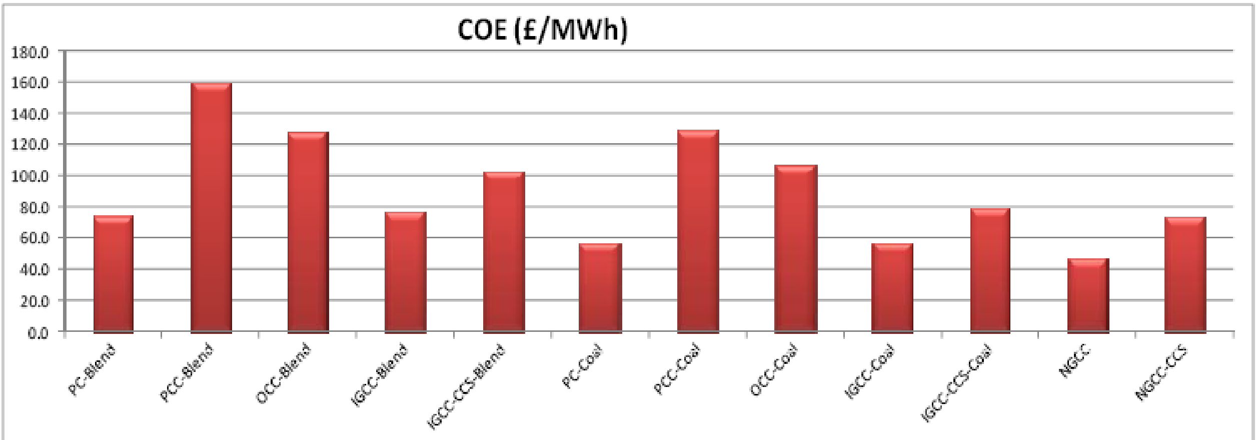


Figure 10: Comparative studies of cost of electricity (CoE) in £/MWh for different combustion technologies.

From the analysis the following points were concluded

- Cost of Electricity is more dependent on the fuel type because of its cost.
- Cases with CCS generate electricity at much higher cost.
- Post-combustion is more expensive than oxy-combustion.
- IGCC slightly more expensive than PC without CCS, but much cheaper with CCS.
- IGCC for blends is more expensive than for coal with and without CCS.
- NGCC again cheaper than the other technologies even with CCS.

For each combustion technology, total power plant lay-out is subjected to conservation of mass and energy principles to evaluate the net thermal efficiency of power plant. For these process simulations, commercially available ASPEN PLUS software is used. From these results it is observed that introduction of CCS significantly reduces the efficiencies in all combustion technologies. The results of these net thermal efficiency calculations based on HHV are given Figure 11. Efficiencies in co-firing cases are comparable to those for coal, although slightly lower. This trend is more pronounced in the IGCC system. NGCC has the highest efficiencies with and without CCS. From this analysis it is claimed that natural gas fired combustion cycle systems require less investment, lower energy penalty and low Cost of Electricity with CCS.

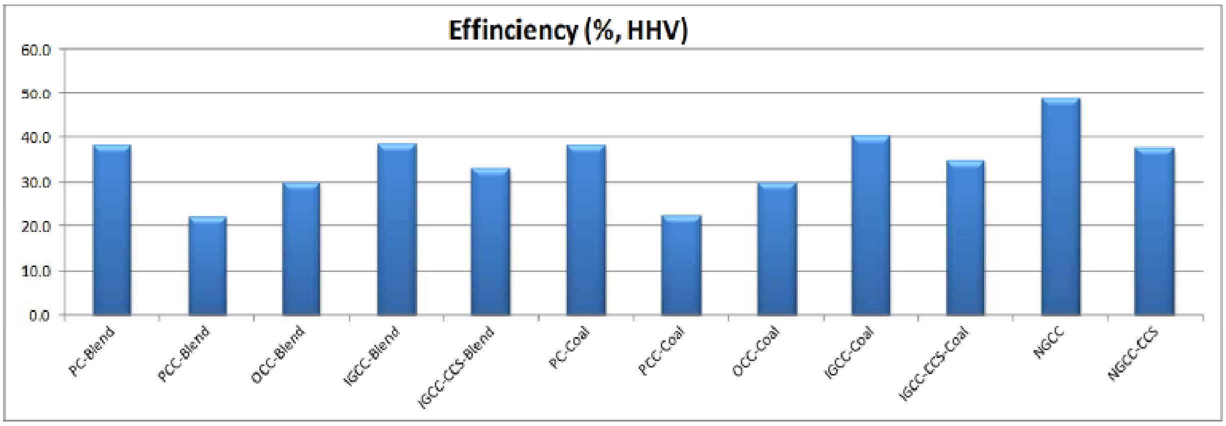


Figure 11: Comparative studies of net thermal efficiency in £/MWh for different combustion technologies.

Second presentation was on CFD activities of the group by Dr. Alessandro Pranzitelli, Research fellow. 1 MW_{th} E.ON test facility to predict and compare air-fired and oxy-fired coal combustion systems was used. These results with experimental observations to validate the CFD simulations were compared. Total geometry and meshing was done using Gambit software, this is shown in Figure 12.

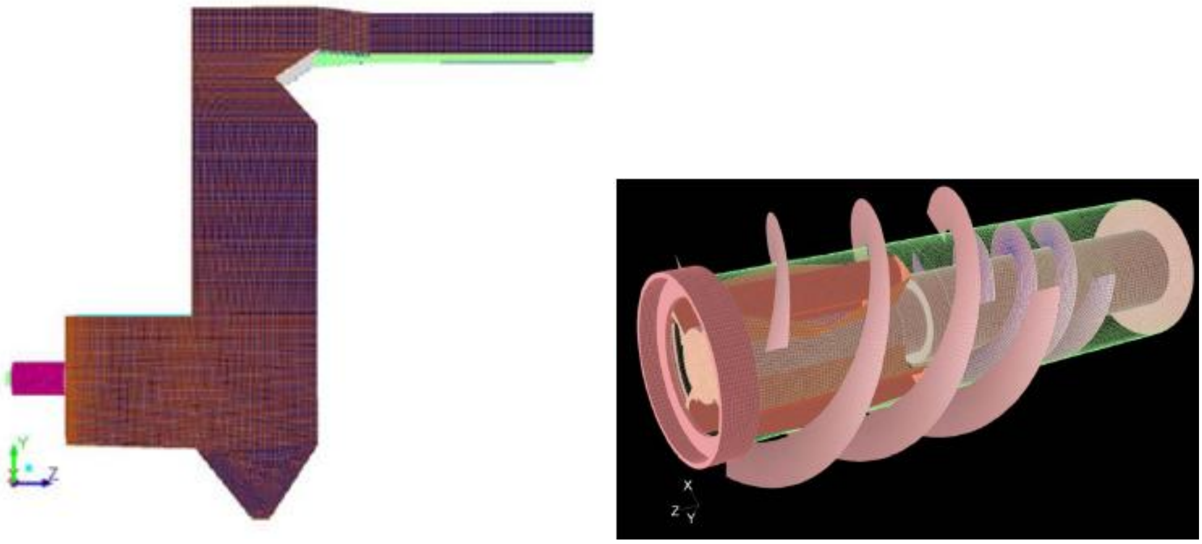


Figure 12: Combustion chamber geometry and burner configuration with meshing for CFD simulations.

Two different turbulence methods have been tested to compare the combustion simulation, one is Reynolds Average Navier-Stokes (RANS) methodology and other one is Large Eddy Simulations (LES) methodology. Commercially available Ansys® Fluent 12.1 was used to carry-out these simulations. The geometry of combustion chamber and burner arrangement is shown in Figure below. Steady state simulations were conducted with k-ε model with standard wall functions model for RANS. The interaction between turbulence and combustion chemistry was accounted using eddy-dissipation model. For coal devolatization kinetics 2-step global reaction was used and for char combustion intrinsic kinetic model was used. Radiation was included in these simulations by using discrete ordinate (DO) model. For LES simulations WALE sub-grid scale model was used, rest of all parameters were same as RANS simulations. RANS simulations were carried out using a 1 quad-core, 2.83 GHz processor and 8GB RAM computer. But, the LES simulations were carried out using ARC1 HPC cluster with 50 intel® Nehalem X5560, 2.8 GHz CPU cores, each core of 2 GB RAM. Since, LES needs high quality mesh to conduct these simulations a CPU cluster is required.

The results of these simulations are compared with experimental data obtained from E. ON test facilities. Figure 13 shows the comparison of side-view of the flame shape between simulations and experimental observations. From these results, it is obvious that a close prediction flame shape is observed between RANS and LES simulations for air-fired coal combustion process.

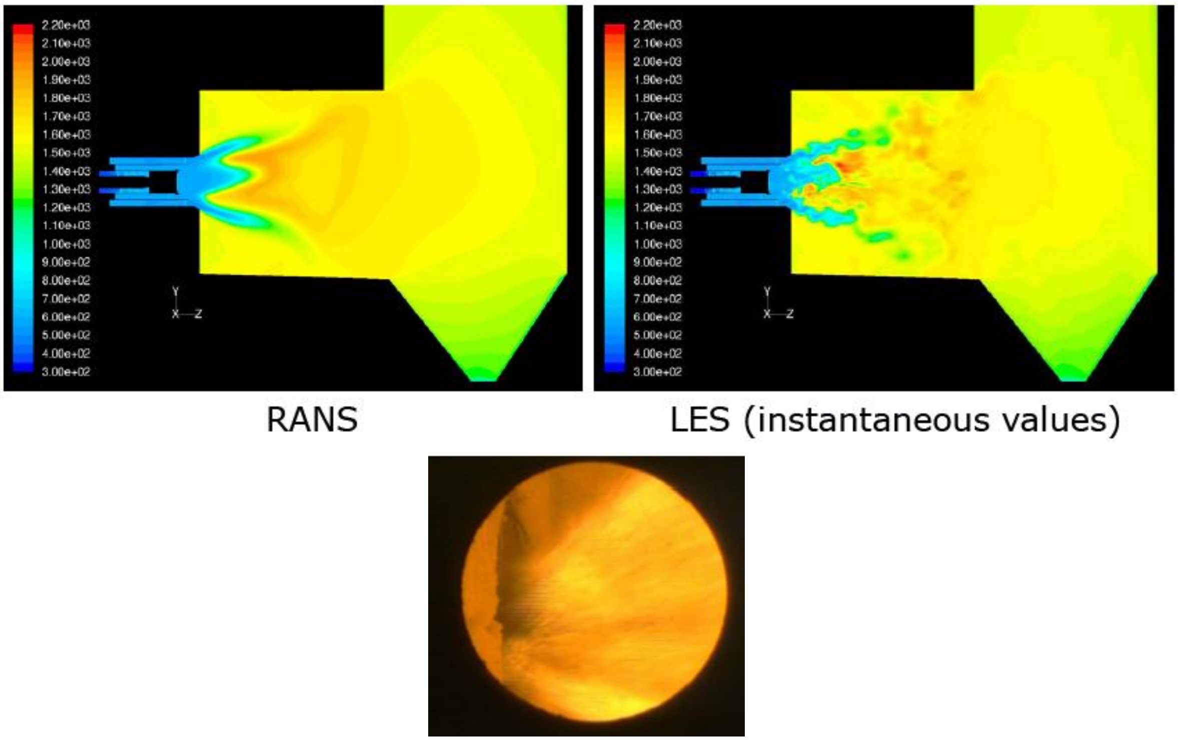


Figure 13: Comparison of predicted and experimental flame shape for air-fired coal combustion system.

Similar comparison is also made in Figure 14 for oxy-coal combustion system using RANS and LES simulations. Close match between predicted and experimental results has been observed from these studies. But, when the measured flame temperature across the combustion chamber compared with simulations of oxy-coal combustion studies (shown in Figure 15) results are over predicted by CFD simulations. However, close match was observed for air-coal combustion temperatures. Among the two turbulence models, results with LES turbulence model predicting flame temperatures are better agreeing with experimental results than RANS predicted flame temperatures. It was concluded that the reason for this deviation was due to inaccurate radiation model used in oxy-coal combustion. It was stated that simple grey model is not sufficient to describe the radiation effect of CO_2 in the oxy-coal flames since, CO_2 has higher absorption capacity than N_2. Therefore, a non-grey gas model (FSK), for better prediction of flame temperatures in oxy-fuel conditions was developed.

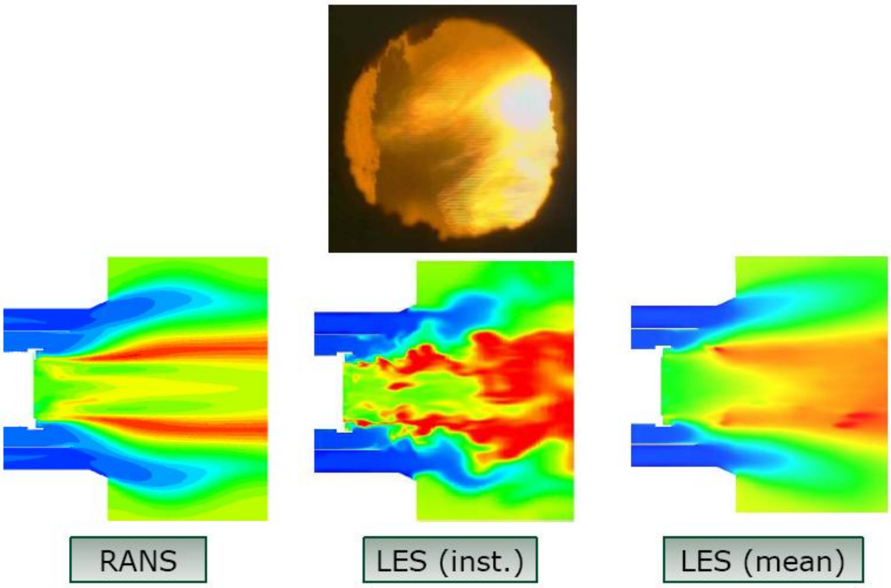


Figure 14: Comparison of predicted and experimental flame shape for oxy-fired coal combustion system.

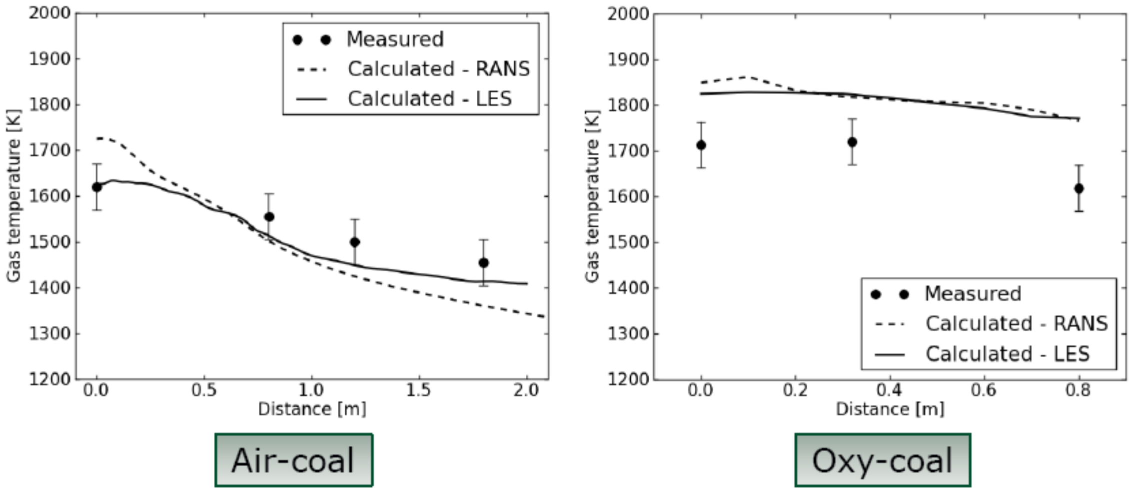


Figure 15: comparison of experimental and predicted gas temperature across the combustion chamber for air-coal and oxy-coal system

The numerical investigation was extended to 500 MWe wall fired coal boiler and carried similar studies with air-coal and oxy-coal systems. Total boiler including super heater, re-heater and other important elements of the boiler for simulations was considered, it has 3.2 million cells and 18 burners firing in the system. During these calculations, O_2 concentration was varied at the inlet of oxidizer in oxy-coal combustion system. Three different O_2 concentrations were tested such as 25%, 30% and 35% and the rest is considered as CO_2 and steam. Temperature and velocity profiles of each of these simulations compared with air-coal combustion system, are shown in Figure 16. From these studies the optimum O_2 concentration in oxy-coal combustion was evaluated. It is observed from Figure 16 that as O_2 concentration increases in the inlet, the peak flame temperature increases in the boiler. It was also observed that in oxy-coal system total flow rates in the boiler are lower than air-coal system. This is due to higher density of CO_2 in oxy-coal combustion, which yields lower volumetric flow rates in the boiler. It was told that another advantage in oxy-fuel combustion is that the volume of boiler reduces significantly for the same thermal power rating.

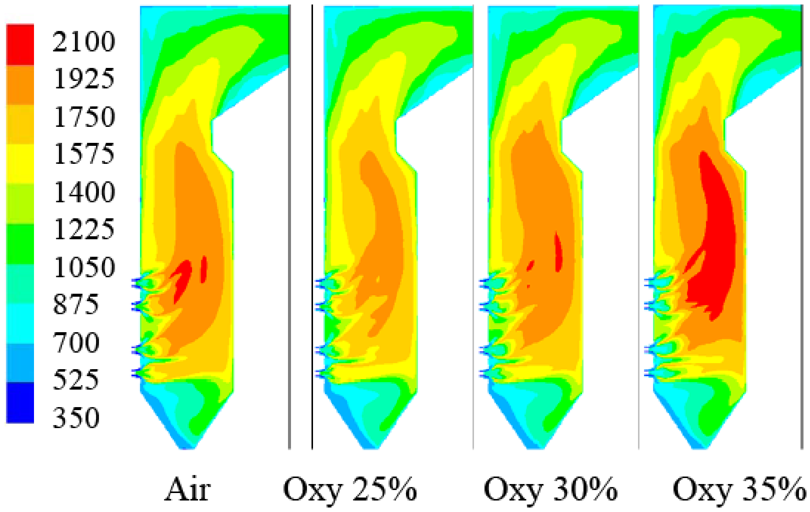


Figure 16: Comparison of temperature profiles for air-coal and oxy-coal systems.

1D model for steam-side heat flux calculations using flow dynamics predicted by CFD simulations is developed. The fluegas temperature and gas heat flux up to reheater is considered to develop this model. For evaluating heat flux coefficient for two-phase flow, the post processed CFD data is fed back to CFD. Based on this model the steam conditions are evaluated at superheater exit for air-coal combustion oxy-coal combustion at different O_2 concentration and compared. Comparison of mass flow and pressure are shown in Figure 17, based on this study it is concluded that for a O_2 concentration between 30-35% in oxy-coal system, steam parameters close to air-coal system can be achieved.

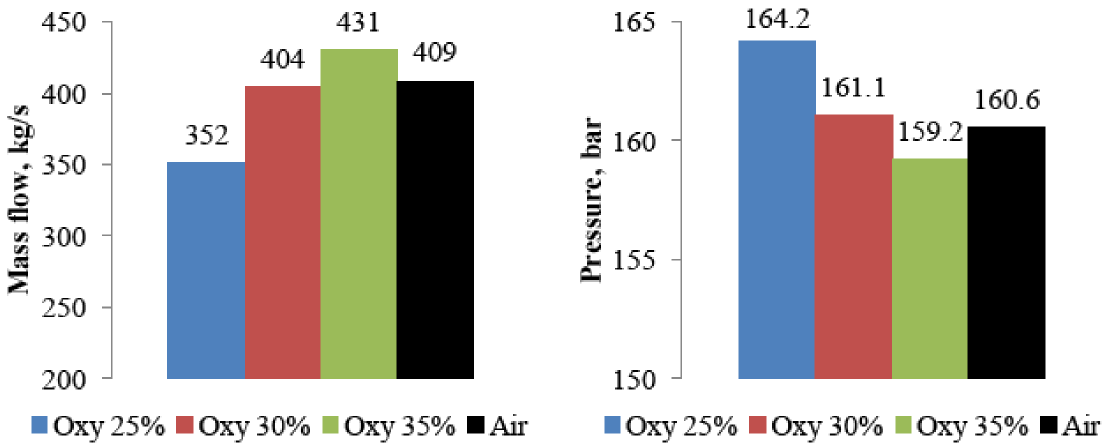


Figure 17: Predicted steam flows and pressures at superheater exit for air-coal and oxy-coal (at different O_2 concentration) combustion systems.

Based on peak flame temperature and tube metal temperature (shown in Figure 18) comparison for air-coal and oxy-coal system at different oxygen concentration has been made. From these studies it is concluded that O_2 concentration between 28 - 33% in oxidizer in oxy-coal system similar metal temperatures as air-combustion can be achieved.

From these studies it is concluded that for retrofitting oxy-coal combustion in air-coal systems, the overall oxygen concentration must be in the range 30 - 33%. This corresponds to 68 - 72% of flue gas recycle in the oxy-coal combustion system.

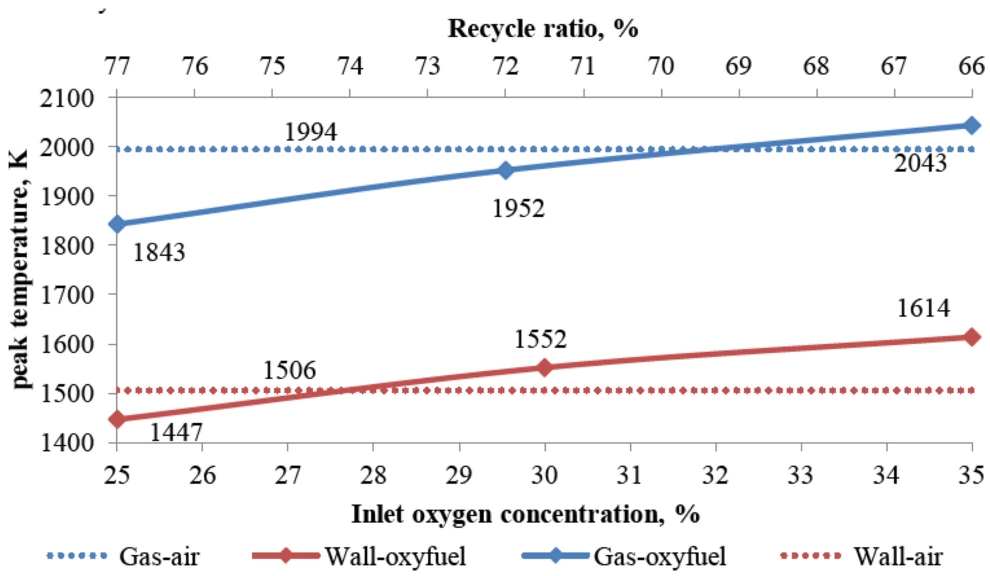


Figure 18: Predicted peak temperatures at wall and near combustion zone air-coal and oxy-coal (at different O_2 concentration) combustion systems.

Third presentation was on pilot scale advanced capture technology (PACT) facilities by Mr. Janos Szuhanszki. The presentation briefed about the experimental tests that are planned at PACT facilities with different systems such as oxy-coal combustion and biomass co-firing studies. Those test results will be used to validate the CFD simulations. As of now the work is mostly on modelling but soon experiments using a 250 kW vertically down-fired combustion chamber with flue gas recycle will be initiated.

In the afternoon the team visited the PACT facilities at Sheffield, Dr. Bill Nimmo accompanied to the facilities. These facilities are located at Sheffield 60 km from Leeds and are funded by Departments of Energy and Climate Change (DECC) to support CCS innovation and technology development.The facilities will become part of the broader UK Centre for CCS umbrella. The PACT consortium includes Edinburgh, Cranfield, Imperial, Nottingham, Sheffield and Leeds universities. The experimental facilities available at this complex is shown in Figure 19.

The team also visited 20 kW down fired combustion chamber, which is claimed as equivalent to drop tube furnace (DTF). It can be used for coal kinetics studies and ash characteristics. A new 250 kW down-fired vertical combustion chamber for oxy-fuel studies with coal is being constructed which is shown in Figure 20. Dr. Bill Nimmo shared that it will be commissioned in the next 6 months time. This experimental set-up is fitted with 2D and 3D cameras to evaluate the flame shape, suction pyrometer to measure gas samples composition and temperature at different locations in the combustion chamber. In addition to these Laser Doppler Velocimetry (LDV) will be used to measure 2D velocity profile at different sections of the chamber. The facility has a post- combustion capture experimental set-up with MEA solution.

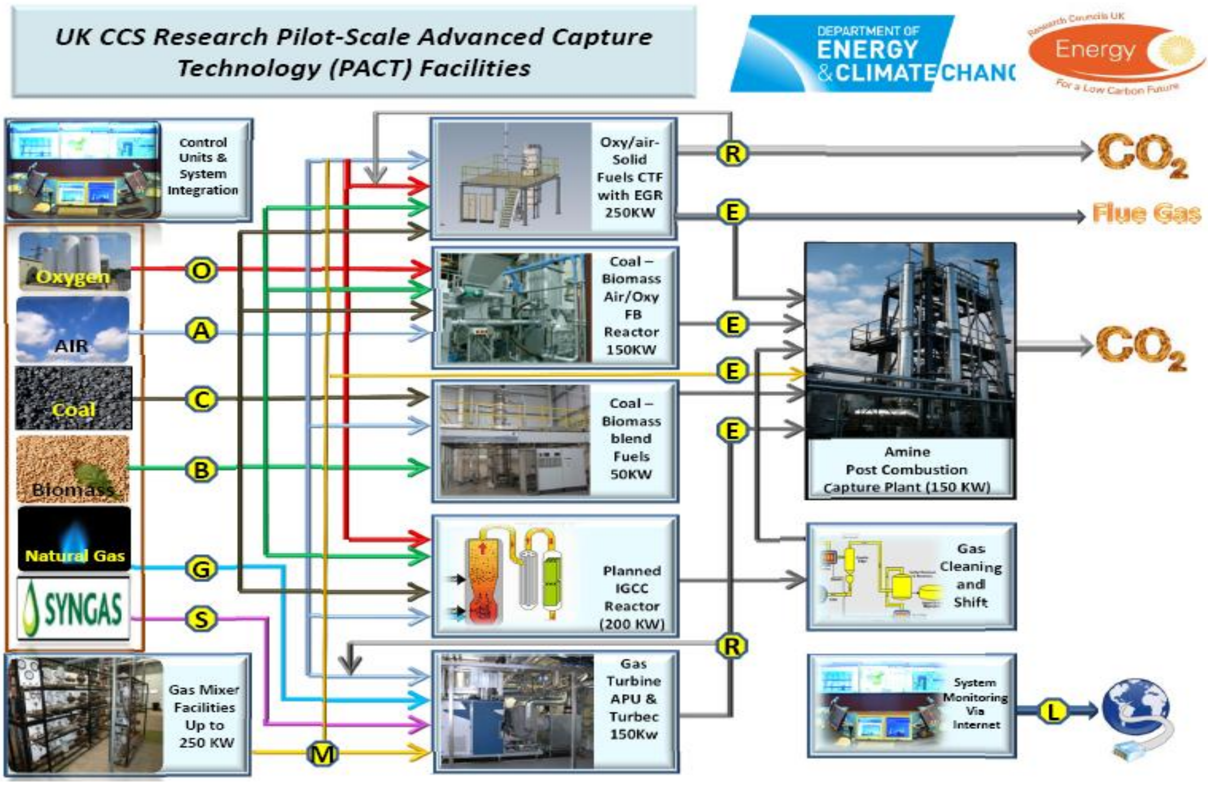


Figure 19: pilot scale advanced capture technology (PACT) facilities at Sheffield.

Figure 20: 250 kW vertically down fired oxy-fuel combustion chamber at PACT facilities, Sheffield.

7. The University of Nottingham

On 15th November, 2012, the team visited the following facilities at the University of Nottingham: Post-combustion CO_2 capture by adsorbents in bubbling fluidized bed and Drop tube furnace and Microscopic image analysis of coal/biomass.

Summary: The team met Dr. Trevor Drage and had a productive interaction on carbon capture by adsorption using polyethalenimine (PEI) - Silica material, template MF resin, sugar carbazole carbon and UF resin carbon. For these materials adsorption takes place at around 40 – 60° C and desorption takes place at 120 – 150 °C. It was claimed that attrition rate is small even for 500 hr cycle time and good capture efficiency is achieved. The team also visited the laboratory test facility.

The team also met, Dr. Huo Liu at the university. He shared with the team many informative analysis and results on the 20 kW oxy-coal combustion experimental investigation. It was shared that in the oxy-fuel combustion, 30% O_2 by volume must be maintained to get stable combustion. The NOx formation is lower in oxy-fuel combustion compared with air combustion. The team visited Dr. Huo Liu's lab which includes CO_2 capture using solid adsorbents test facility and bubbling fluidized bed combustion (BFBC) test facility. For BFBC, biomass is used as fuel and the syngas is cleaned using solid adsorption technology. It was claimed that efficient cleaning can be achieved using adsorbent technology.

The team visited the DTF facility along with Dr. Drage which is 1.5 m tall and it has 600 ms residence time. Biomass reactivity and oxy-coal combustion was evaluated. It was shared that char burn-out in 600 ms was about 40%. The team also visited the CCSEM facilities in lab; the CCSEM with EDAX is used mostly for ash analysis. Coal and biomass mineral matter analysis is also being carried out.

On 16th November, 2012, the team met, Prof. Ed Lester, an expert in the area of Petrography analysis and microscopic image analysis and who has also developed an index to determine whether the given coal fires well or not. Different methods used to determine coal macerals, vitrinite/inertinites and coal/char reactivity were discussed in detail. Based on image analysis, it is claimed that it is possible to predict whether the given coal would perform well in boiler or not.

Next the team had an interaction session with Dr. Robin Irons from E.ON Company. He discussed in detail about the option of the 1 MW_{th} oxy-coal combustion facility at Ratcliff, 10 km away from Nottingham. EON is also currently executing a 250 MWe retrofitted post-combustion CCS power plant project in Maasvlakte, Rotterdam, Netherlands. It is a joint venture (JV) between E.ON and GdF Suez, where EON is transporting CO_2 around 25 km before it is being sent for storage at 3.5 km below the sea level. The power plant site under construction at Maasvlakte is shown in Figure 21 below. From this facility the project is planning to store around 1.1 Million Tonnes of CO_2 per year.

Figure 21: E.ON's post-combustion CCS power plant (under construction) at Maasvlakte, Netherlands.

Dr. Robin Irons shared their experience and operation problems encountered during 1MWth oxy-coal combustion experimentation. The schematic arrangement of the total experimental set-up is shown in Figure 22. The horizontal refractory lined and water cooled combustion chamber for oxy-coal tests is used. Part of flue gas is recycled and then split into three parts such as primary oxidizer, secondary oxidizer and tertiary oxidizer, the primary oxidizer temperature is maintained between 70 - 90 ^{0}C and secondary and tertiary oxidizer at the wind box is maintained between 280 - 330 ^{0}C. Overfire air is used to reduce NOx formation. The primary oxidizer is either unmixed or partially mixed with O_2. To avoid water formation in the coal carrying line the primary oxidizer is cooled down to 5 ^{0}C where most of the water vapour condensed in the oxidizer which is then preheated to 70 - 90 ^{0}C before sending for coal transportation to burner. Dr. Robin Irons shared that wet oxidizer causes water formation near the first contact between coal and oxidizer. This may potentially block the coal carrying line. It was suggested that O_2 in the primary oxidizer must be less than 20% to avoid any fire in the coal line. It was also mentioned that people who used high O_2 concentration (up to 40%) in the primary flue gas line had the problem of ignition in the feed line.

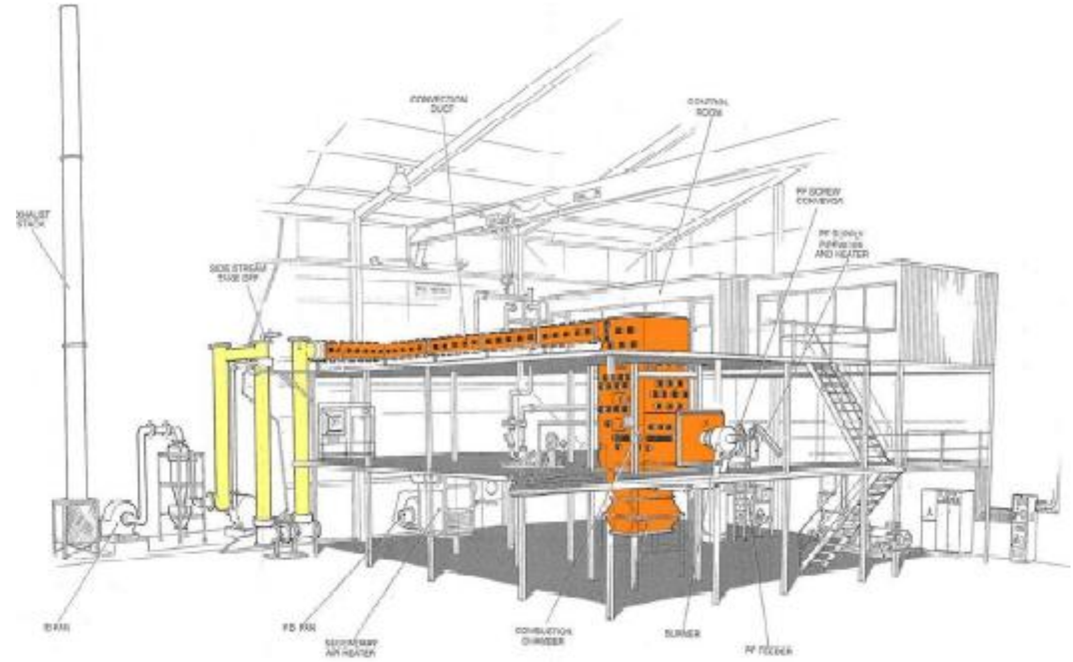


Figure 22: Schematic representation of E.ON's 1 MW_{th} oxy-coal combustion test rig.

The secondary and tertiary oxidizer is maintained at slightly higher O_2 concentration than required to compensate less O_2 flow in primary oxidizer. It was told that the overall O_2 concentration in the oxidizer is varied between 21% and 30 %. Two different types of coals for their experimentation were used such as El cerrejon and Thoresby. Both are low moisture and low ash content coals. El cerrejon (0.7, 0.02% dry basis) is low sulphur, low chlorine coal and Thoresby is high sulphur, high chlorine (1.9, 0.5% dry basis) coal. Detailed analysis of these coals and calorific values are given in Table 4 below.

Table 4: Comparison of coal properties used in E.ON's 1 MWth oxy-coal combustion test facility

	El Cerrejon	**Thoresby**
Net CV (kJ/kg)	27122	27393
Moisture content (% AR)	5.8	4.8
Ash content (% dry)	9.1	12.4
Volatile matter (% DAF)	40.7	38.7
C (% DAF)	80.8	82.4
H (% DAF)	5.1	5.1
N (% DAF)	1.7	1.9
S (% DAF)	0.7	1.9
Cl (% DAF)	0.02	0.5

Using both coals, corrosion studies were carried out in the combustion chamber. For conducting these studies air and water cooled probe were used, this probe is fixed in the wall at the end different metal specimen were fixed for testing. These specimens were kept on the furnace walls for about few hours and analyzed in the lab. CCSEM images were used to analyze the intensity of the corrosion for each material. The corrosion test rod is shown in below Figure 23. Based on corrosion testing propensity of corrosion were plotted for different materials at different temperature for air-coal and oxy-coal combustion with two different coals. These Figures are shown in Figure 24 -26.

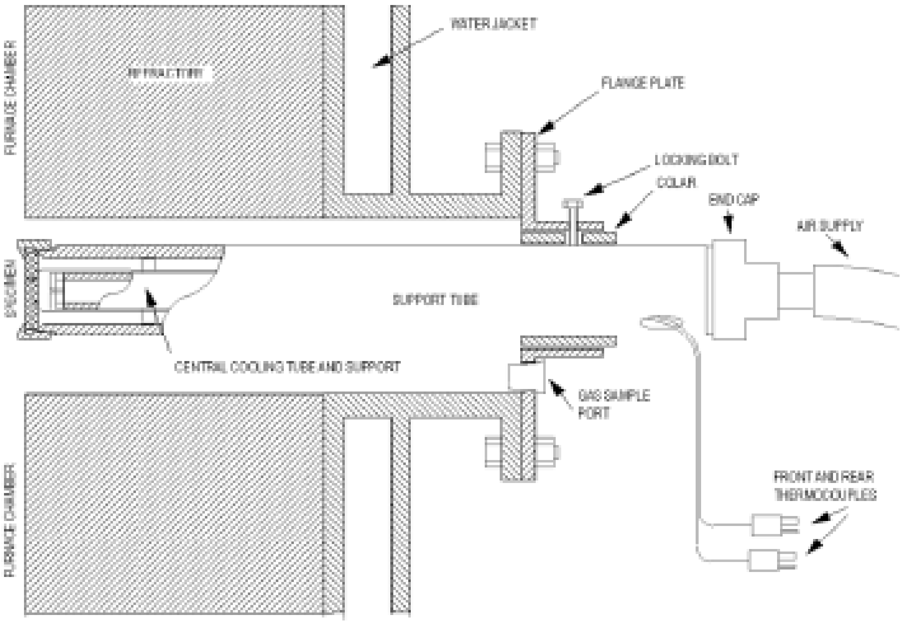


Figure 23: Corrosion test rod for testing different material in air-coal and oxy-coal combustion experimentation.

From Figure 24, it can be observed that only T22 material affected by air-El cerrejon coal combustion but the other metals such as E1250, TP347HFG and HR3C are not affected during air-El correjon coal combustion. Similar testing has been repeated for oxy-El cerrejon coal combustion. From these results (Shown in Figure 25) it can be seen that during oxy-coal combustion T22, T91 got effected but other materials are E1250, TP347HFG, HR3C, San25, and IN740 (Inconel) are not corroded.

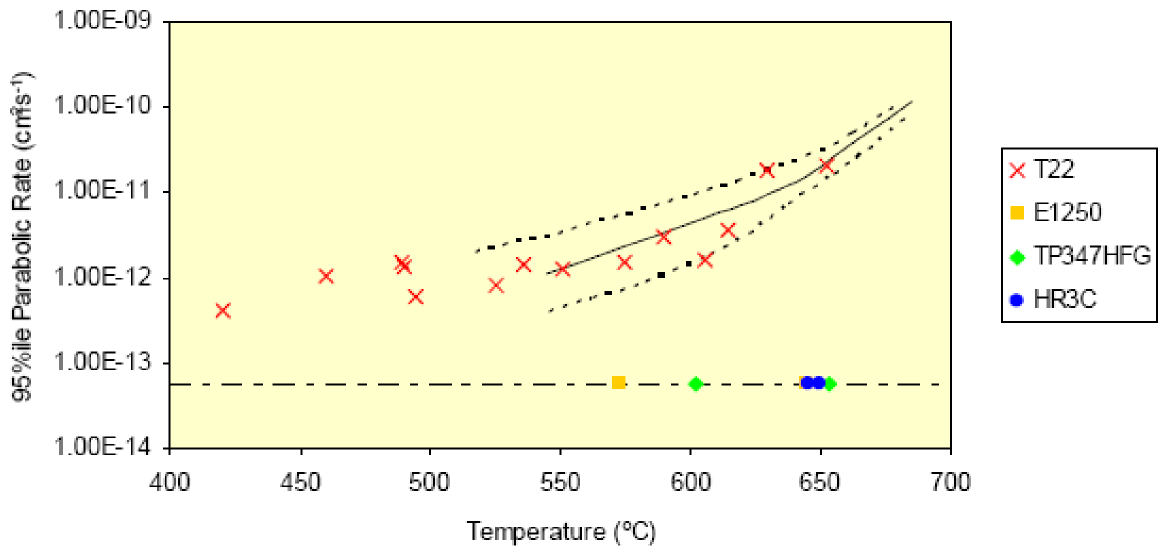


Figure 24: Corrosion studies with different material for air-coal combustion with El cerrejon coal.

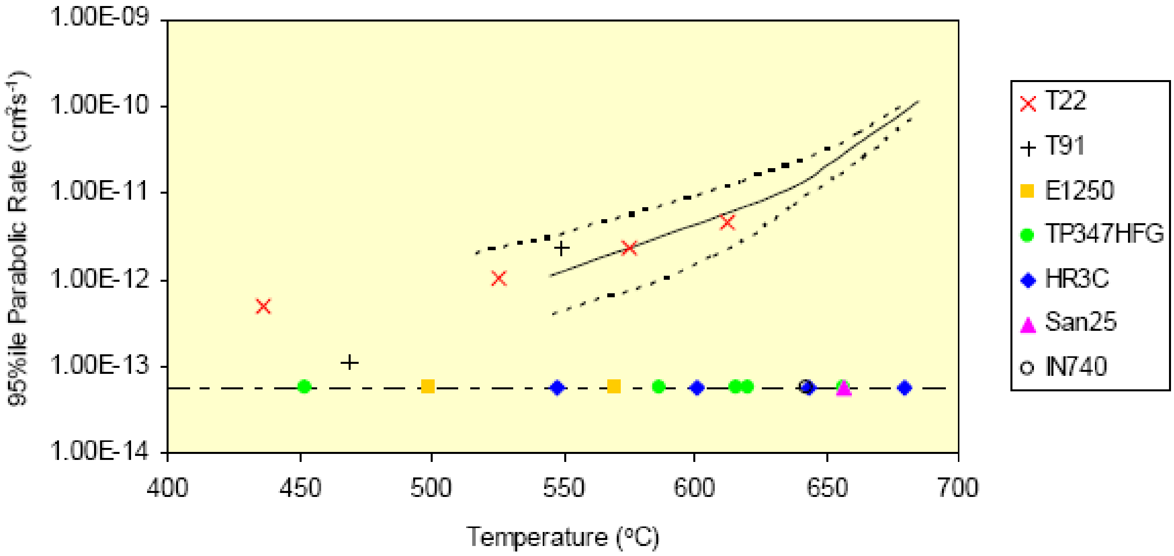


Figure 25: Corrosion studies with different material for oxy-coal combustion with El cerrejon coal.

Corrosion tests are also conducted for oxy-Thoresby coal combustion these results are shown in Figure 26. From these results it can be seen that almost all mate,rials including inconel got corroded during these experimentation. The reason for this can be partially attributed to high sulphur and high chlorine content in Thoresby coal than El cerrejon coal. Mr. Robin Iron shared that oxy-fuel combustion has more corrosive atmosphere than air-combustion. It was also hinted that possible corrosion by CO_2 in oxy-fuel combustion mode. Since oxy-coal combustion is more corrosive in nature it was suggested that after each oxy-coal experiment, one must pass air in the recycle line and combustion chamber for 30 to 60 min to avoid sulphur/chloride deposits.

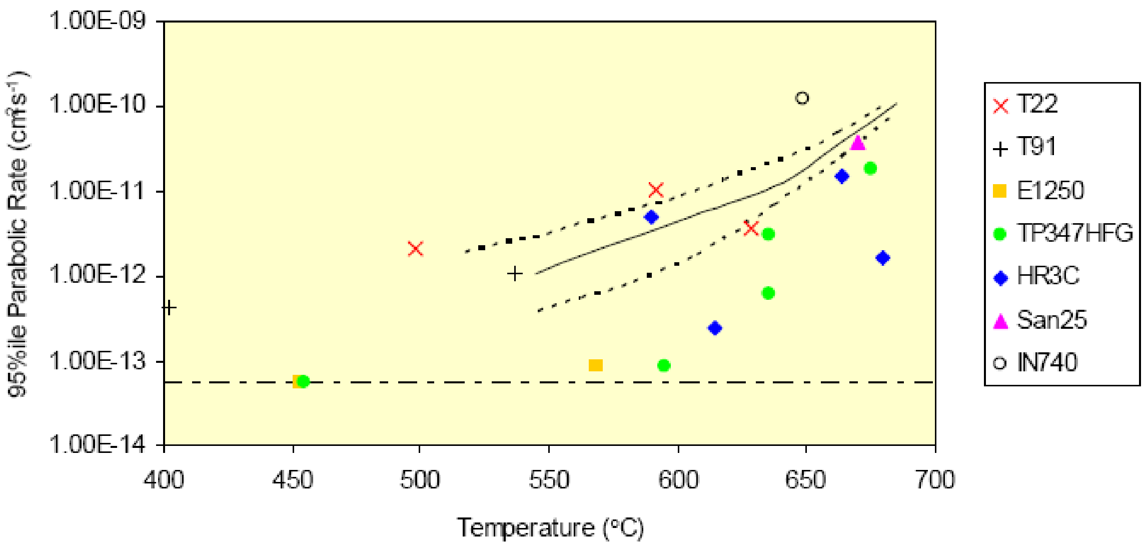


Figure 26: Corrosion studies with different material for oxy-coal combustion with Thoresby coal.

Team interacted with the below list of experts during the Internship visit:

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16.	**Dr Hao Liu,** Associate Professor, Institute of Sustainable Energy Technology	The University of Nottingham	+44(0)1158467674 liu.hao@nottingham.ac.uk

ANNEXURE

Picture: Discussion with Dr. Bill Nimmo and Dr. Lin Ma at ETII office at Leeds University.

Picture: Discussion with Dr. Paul Fennel in Imperial College London.

Picture: Discussion with Dr. Collin Hale at post-combustion CCS facility in Imperial College London.

Picture: Discussion with Mr. Robin Irons and Dr. Trevor Drage at Nottingham University, UK