Experimental investigation with PACT facility and CFD modelling of oxy-coal combustion with recycling real flue gas

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Project Dates: August 2013 – March 2017

Background / Project overview
Oxy-coal combustion technology has gained confidence and maturity especially within the last decade (Santos S. 2012) compared to the much earlier studies (Kimura et al., 1995; Wang et al., 1988). However, there are still a number of research challenges associated with flue gas recycling, gas clean-up and plant scale tuning of CFD models and hence plant-scale tools. The measured gas concentration profiles of the 250kWth PACT oxy-coal combustor will allow CFD modellers to validate and develop the NOx prediction models further for oxy-fuel combustion.

Key Findings
- 250kWth combustion tests (Figure 3a-b): (1) NO injection (200-1000 ppm) through all the balance oxidant in air case resulted in 80% destruction of injected NO, due to existence of fuel rich zone; NO injection in Oxy 28% combustion tests resulted in 79%-82% NO destruction (Daood et al., 2015).
- CFD modelling: (1) In the chemically developed regions of the external recirculation zones in air, the NOx predictions show a similar qualitative trend with the major species, with the CH2 burning analogue clearly showing a very good agreement away from the flame (Figure 3c); (2) In Oxy 28% case the CH4 analogue shows some differentiation from the case with no reburning and appears to achieve a closer agreement with the experimental measurements (Figure 3d-e) (Daood et al., 2015).
- V-DTF ignition tests (Figure 3f): V-DTF combined with a high speed imaging technique can be successfully used to characterise the ignition of pf particles (Bai et al. 2016); in air case, ignition distance depends on coal rank as expected (Sarroza et al., 2016).

References
Daood S.S., et al. 2015. Experimental investigation and CFD modelling of oxy-coal combustion on UKCCSRC- pilot scale advanced capture technology
www.ukccsrc.ac.uk

Avenues for exploitation
- The measured gas concentration profiles of the 250kWth PACT oxy-coal combustor will allow CFD modellers to validate and develop the NOx prediction models.
- In addition, in-flame measurements with the 250kWth PACT oxy-coal combustor (temperature and gas concentrations) will provide further data for the fine tuning of CFD models and hence enable CFD models to become more useful plant-scale tools.
Multiphase flow modelling for hazard assessment of dense phase CO₂ pipelines containing impurities

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Project Dates: May 2013 - September 2014

Aims and objectives

The aim of the project is to develop and validate experimentally a heterogeneous flow model for predicting the transient depressurisation and outflow following the puncture of dense-phase CO₂ pipelines containing typical impurities.

Given that CO₂ is an asphyxiant at high concentrations, this information is pivotal to assessing all the hazard consequences associated with CO₂ pipeline failure, including fracture propagation behaviour, atmospheric dispersion, emergency shutdown valve dynamics and emergency blowdown.

Experimental background

Model validation is performed by comparison against the data from small and large-scale experiments performed in the CO2PipeHaz FP7 project, and the field data generated in the National Grid COOLTrans project.

Mathematical model of the flow

The time-dependent flow model accounts for:
• Thermal relaxation model for flashing CO₂ liquid
• Two-phase separated flow model

The conservation equations of the model are:
\[
\frac{\partial (\alpha_i \rho_i \vec{v}_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \vec{v}_i \vec{v}_i) = S_p
\]
\[
\frac{\partial (\alpha_i \rho_i \vec{v}_i \vec{v}_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \vec{v}_i \vec{v}_i) + \nabla (\alpha_i p) = \rho \nabla \alpha_i + S_v
\]
\[
\frac{\partial (\alpha_i \rho_i E_i \vec{v}_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i H_i \vec{v}_i \vec{v}_i) = -p \frac{\partial \alpha_i}{\partial t} + S_e
\]

Full bore rupture results

Progressing to the next technology level readiness level requires:
1) Further research involving the improvement of the flow model to encompass a wider range of flow phenomena such as nucleation of bubbles in liquid and incipient condensation of the vapour.
2) Validation of the flow model through the comparison of its predictions against data obtained using the rupture of realistic scale CO₂ pipelines.
3) Translation of the flow model into a robust computer programme and its commercial exploitation through licensing.

Publications from the project

Fault Seal Controls on Aquifer CO₂ Storage Capacity

Principal investigator: John Williams  
Co-Investigators: Stuart Haszeldine, Andy Chadwick  
Key researchers: Gareth Johnson  
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Project Dates: September 2013 - January 2016

Project overview

Structural traps for storage of supercritical CO₂ will commonly rely on a component of fault seal. Faults are among the most important natural potential migration pathways for buoyant fluids stored in reservoir rocks. Failure of storage integrity may occur either by mechanical failure or by flow across faults due to geometric juxtaposition of the reservoir against similarly permeable rocks and/or lack of a low permeability fault gouge.

This project aimed to reduce uncertainty relating to the sealing capacity of faults affecting prospective North Sea saline aquifers, by:

• Studying the controls on fault seal capability in naturally-occurring fault-bound CO₂ accumulations (Fizzy and Oak)
• Assessing the geomechanical stability of faults affecting an important saline aquifer offshore UK (Captain Sandstone)
• Investigating the characteristics of apparently hydraulically-conductive faults in the North Sea (Netherlands)

Research highlights

In order to analyse the conditions under which CO₂ is retained in the fault-bound Fizzy and Oak fields, we modify standard fault seal approaches to account for the different physical and chemical properties of CO₂ to oil and methane. In particular the impact of IFT and contact angle on threshold capillary pressure is investigated.

Fig 1. Fault plane diagram showing threshold capillary pressure for the Fizzy field fault. Note the reduction in sealing capacity immediately below the GWC which explains the lack of full structural fill.

We also examined the geomechanical stability of faults affecting the Captain Sandstone aquifer of the Inner Moray Firth. A detailed analysis of the in situ stress field was implemented using hydrocarbon well data from the region. Integrating this information with a 3D model of the fault network allowed the shear and normal stresses acting on the faults to be resolved, allowing an assessment of their stability.

Fig 2. Slip tendency (ratio of shear to normal stress) acting on faults. Orange surface shows the top Captain Sandstone saline aquifer. Higher values closer to 0.6 are most susceptible to reactivation under elevated pore fluid pressure (as expected to occur during injection of CO₂). The results are shown for a ‘worst case’ scenario where differential stresses are highest. Less conservative cases considering normal-faulting stress regimes show that faults are likely to be less susceptible to failure.

We assessed the nature of several fault-associated bright spots observed on seismic data offshore Netherlands to elicit the characteristics of faults that have potentially allowed the leakage of natural hydrocarbons from deeper source areas/reservoirs.

Key findings

• Using a shale-gouge ratio and modified Sperrevik approach with site specific data and an air/mercury to CO₂/brine capillary pressure equation, we accurately predict the observed column heights at the Fizzy and Oak fields.
• Juxtaposition of the reservoir against Permian carbonate beds may have allowed cross-fault migration of the CO₂-rich gas, explaining the lack of fill-to-spill.
• The storage capacity of the Captain Sandstone aquifer is potentially limited by the potential for fault reactivation, however few pre-existing faults are preferentially orientated for failure in the current stress regime.
• Uncertainty regarding the in situ stress conditions are accounted for by assuming the worst-case scenario in our analysis, so greater pore pressure increase can be accommodated if lower prevailing differential stresses are assumed.
• Faults coincident with bright spots offshore Netherlands are those formed in Palaeogene and Neogene deltaic systems associated with relatively recent salt-related tectonism.

Use of outcomes

Assessing and understanding the conditions under which faults may be sealing or transmissible to fluid flow in a variety of North Sea settings is important in terms of understanding and mitigating against risks to storage site integrity. It is hoped that the results of this project will be of use to a range of CCS stakeholders, including the private sector, government, regulatory bodies and the academic community. We have demonstrated that pre-existing faults, considered to be one of the principal risks to CO₂ storage site security can be evaluated in such a way as to mitigate against unintentional CO₂ migration.
Flexible CCS Network Development (FleCCSnet)

Key researchers: H. Aghajani and E. Sanchez Fernandez

Project funded by the UKCCSRC as part of its Call 1 for Research Proposals, in partnership with Newcastle University, the University of Edinburgh and the University of Strathclyde

Project Dates: October 2013 - August 2015

Project overview

The aim of the project was to carry out research to enable the production of design and operating guidelines for CCS pipeline networks in order that these networks can react effectively to short, medium and long term variations in the availability and flow of CO₂ from capture plants and also to the constraints imposed on the system by the ability (or otherwise) of CO₂ storage facilities to accept variable flow.

The amount of CO₂ captured at a power station is expected to become more variable in the future as the electricity grid brings in more and more intermittent renewable energy (meaning a conventional power station is temporarily not needed or in reduced operation as the renewable energy takes precedent). The storage site will also face periods of maintenance which will impose constraints on the flow into the store and it is also important to look at the case of upset conditions in order to be able to predict any potential problems. Solutions to all these issues need to be factored into the design of the CCS network, the focus of the project was to identify the issues surrounding flexibility and explore some of them.

Deliverables

- Delivery of two practitioner workshops during the course of the project;
- Publication in academic journals and industry-relevant peer-reviewed conferences
- Presentation of the guidelines and data generated by the project intended for stakeholder use on the UKCCSRC website.

Research highlights

The publication output will consist of five journal publications— three published [1, 2, 3], one currently in internal review and one submitted for GHGT-13—and two peer reviewed conference talks.

To ensure industrial relevance and rapid and effective dissemination to relevant stakeholders, two workshops were held during the duration of the project, the first in Edinburgh on 30 April 2014 and the second in Newcastle on 22 April 2015.

Workshop 1 Key Findings:

- Critical variables were identified and are listed in Table 1.
- Scenarios were split into short, medium and long term (Periods 1, 2 and 3) and the type of store to be used – A, B and C – see Figure 1.
- The findings of Workshop 1 are summarised in two documents available on the UKCCSRC website.
- Base load power plant data and a shifting pattern for a 24 hour were provided by Scottish Power for use with the project.

Workshop 2 Key Findings:

- Scenarios with EDR should currently be neglected within the project.
- Short term scenarios should be investigated in terms of pipeline line packing time to investigate issues that could result from smaller emitters entering the network in Period 3.
- The project’s storage model could be used as a screening of storage fields based upon the pipeline’s ability to be able to take up storage limitations.
- Guidelines should be made available on the best practise for entry into a CO₂ pipeline network.
- Information on well head conditions were provided by National Grid for use by the project.
- Cost data for use by the project provided by Costain.

Key findings/outcomes

Most studies are based on simplifying assumptions about the capabilities of power plants to operate at part load to and to regenerate additional solvent after intermittent storage of solvent. [1] addresses this gap by examining the operational flexibility of supercritical coal power plants with amine based CO₂ capture, using a rigorously fully integrated model. This provides rigorously validated guidelines for the increasing number of techno-economic studies on power plant flexibility, and CO₂ flow profiles for studies on integrated CO₂ networks.

[2] characterises the operating envelope, the performance and the corresponding compressed CO₂ flow of coal power plants for a range of loads, with or without voluntary by-pass of the capture unit. Optimised part-load operating strategies provide novel insights into the additional capabilities of CCS power plants specifically designed for enhanced operating flexibility.

[3] was written in response to the recommendations of Workshop 2. Various store properties, such as subsurface conditions, permeability and pressure response to CO₂ injection, that have a key impact on store performance were evaluated for a selection of delivery and storage scenarios identified in Workshop 1. The effect of uncertainty in storage capacity was investigated in order to accommodate a range of CO₂ flow. Planning CCS infrastructure needs to address the impact of store uncertainties and store flow flexibility on infrastructure costs and availability. The results provide detailed insight on the expected impacts of store properties on transportation infrastructure performance. The analysis indicates that wellhead conditions are substantially influenced by subsurface conditions.

Short term effects on the pipeline are being investigated in terms of line packing capacity as requested in the Workshop 2 discussions. The work looks at the parameters that could impact line packing time for CO₂ pipelines. The time is estimated based on the time it takes for pipeline’s internal pressure to reach its maximum operating pressure (MAOP). Line packing time is shown to linearly correlate to the pipeline length and the gradient of this line increases as internal diameter increases. Formulas for estimating line packing time is given.

Finally a summary of the FleCCSnet project and guidelines on best practise for the entry into flexible and plausible CO₂ transport networks will be published. The networks will have the ability to react to changes in the flowrate of CO₂ across the whole CCS chain and network design; allowing network designers to anticipate potential problems associated with the operation of the pipeline network.

Use of outcomes/Avenues for exploitation

The findings from the project can be used to ensure CCS infrastructure is designed with flexibility in mind. This includes line packing time, how to best flexibly operate amine capture facilities and the impact of store uncertainties. Potential end users include policy makers, network designers and stakeholders.

References

Mixed matrix membranes for post-combustion carbon capture

Principal investigator: Maria-Chiara Ferrari  Co-Investigators: Stefano Brandani
Key researchers: Nicholas Bryan
Project funded by the UKCCSRC as part of its Call 1 for Research Proposals in partnership with the University of Edinburgh
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Project Dates: April 2013 - April 2016

Project overview

• This work aims to develop an understanding of the gas transport mechanisms within mixed matrix membranes focusing on membranes for post-combustion carbon capture.
• Separation of carbon dioxide from combustion flue gases using selective membranes show promise to be a low energy carbon capture option and is proven as a commercially viable gas separation technology.
• Membranes potentially offer significant energy savings over the currently more developed amine-based absorption technologies.
• Mixed matrix membranes (MMMs) are composite materials comprised of particulate fillers in a polymeric matrix.
• Polymer membranes exhibit a trade-off between permeability and selectivity. By adding fillers the gas separation properties of the membrane can be altered and improved.
• MMMS are fabricated from various materials and the gas permeation properties tested such that the interaction of phases can be investigated.

Research highlights

• PEBAX and ZIF-8 membranes were produced in collaboration with Deakin University. Membranes were successfully synthesised up to a loading of 7.5 wt.%.
• ZIF-8 is a zeolitic imidazolate framework containing cavities connected by small windows which may allow for a molecular sieving effect to occur. [5]
• Permeabilities of He, N₂, and CO₂ were determined using the constant volume - variable pressure technique at 30°C.

Key findings

• Significant clustering was observed in membranes in and above 5 wt.% ZIF-8.
• Out with the clusters there is still good dispersion of nano particles.
• Voids within clusters is likely to play a role in the large increases in permeability seen at higher loadings.
• The 10 wt.% ZIF-8 membranes produced were too fragile to test but SEM images suggest the nano particles are mobile during the drying phase.

Use of outcomes

• Understanding of the formation of the membrane’s and cluster from the project will be used to produce the next generation of MMMS. Different production routes are under investigation with Australian partners. MMMS could be used in commercial membrane separation units as part of a larger separation system.

References


www.ukccsrc.ac.uk
QICS2 Scoping Project: Exploring the Viability and Scientific Opportunities of a Follow-On Marine Impact Project

Principal investigator: Mark Naylor  Co-Investigators: Jeremy Blackford, Henrik Stahl, Stuart Haszeldine and Stuart Gilfillan
Key researchers: Jen Roberts and Neil Burnside
Project funded by the UKCCSRC as part of its Call 1 for Research Proposals, in partnership with the University of Edinburgh, Plymouth Marine Laboratory and Scottish Association of Marine Science.
Project Contact: Jen Roberts, jen.roberts@strath.ac.uk, +44 (0) 141 548 3177;  Project Dates: January 2013 - July 2013

Project Context
The world’s first sub-seabed CO₂ release experiment was completed in 2014, offshore from Oban (Scotland). The project, known as QICS (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Storage), mimicked the formation of a small-scale CO₂ leak into sediments near the seabed.

![Figure 1: QICS project set-up: A deviated borehole was drilled from the shore to 350m offshore, where the tip of the bore was located 11m below sea floor and beneath 12m of seawater. CO₂ is released via a diffuser into the marine sediments.](image)

A schematic of the site set-up capable of injecting CO₂ into marine sediments is shown in Figure 1. In 2012, CO₂ was continuously injected into the sediments for 37 days, releasing a total of 4.2 tonnes of CO₂. The QICS1 experiment was first of its kind, and was highly successful, enabling:

- field testing of monitoring technologies to detect CO₂ against a measured baseline
- assessment of environmental and ecosystem impacts of leaked CO₂ (within the sediment and water column)
- the flow and fate of CO₂ in sediments, and dispersion and dilution of CO₂ in seawater, to be explored.

Project Aims
There is a compelling case for continued use of the site, building on the learnings from QICS1.

This scoping project explored the viability and potential scientific goals for a follow on CO₂ release experiment. The project aimed to provide information on:

1. Scientific priorities for future experiments.
2. Potential offshore monitoring technologies that could be developed or deployed, including new sensor technology, and chemical tracers for CO₂
3. Opportunities for collaboration, including with international partners and stakeholders.

Research Highlights
Consultations were carried out in Spring 2013 to scope priorities for future experiments; with QICS researchers, and with the global CCS community (representing groups from industry and research organisations). In addition, industrial marine sensor specialists were consulted to explore their interest in a facility for testing sensors and also to review current technology developments (in e.g. submarine geolocation).

A database of controlled CO₂ release experiments (thirteen field and nine lab) was compiled, including information about the experimental design, technologies deployed, and findings at these sites. This is complemented by a global dataset of natural CO₂ seep studies.

A report on geochemical tracers was prepared, which explored their potential applications at QICS. This included a review of CO₂ tracer injection studies, and assessment of the constraints posed by the experimental context, and also aspects such as cost, sampling procedure, environmental issues and regulations.

Key Findings and Next Steps
There are research questions outstanding from QICS1 which future experiments can address. This scoping project found that future experiments would need to seek permissions from regulators and stakeholders, since the site was only approved for one experiment. A thorough baseline survey would also be needed to assess whether the site is affected by residual effects of the previous CO₂ experiments, and so decide if a new borehole must be drilled.

This project also identified that a future experiment should:

- Release CO₂ over a longer period. Though opinions are mixed about the recommended rate of CO₂ injection.
- Build on the QICS1 aims, and so further techniques for measurement, monitoring and detection of CO₂ leakage and explore the longer term effects of CO₂ release.
- Trail methods of quantifying the fate of the CO₂, and geochemical tracers in particular. Candidate additive tracers have been identified, however further work is needed to inform the experimental procedure.
- Facilitate and manage collaboration and technology testing by e.g. inviting interested parties (research and industry) to prepare an Expression of Interest.

References

Other QICS outputs are detailed on the project website http://www.qics.co.uk
CO₂ storage in Palaeogene and Neogene hydrogeological systems of the North Sea: preparation of an IODP scientific drilling bid

Principal investigator: Maxine Akhurst
Co-investigators: Mark Wilkinson, Stuart Haszeldine

Key researchers: Heather Stewart, Margaret Stewart, David Evans, Chris Gent, Sam Holloway, Juan Alcalde, Niklas Heinemann and Rachel Lamb

Project funded by the UKCCSRC as part of its Call 1 for Research Proposals, in partnership with the British Geological Survey, University of Edinburgh and Norwegian academic and industry consortium

Project Contact: Maxine Akhurst, mca@bgs.ac.uk, +44 (0)131 6500285
Project Dates: February 2013 to May 2015

1. Project overview

The North Sea Basin (NSB) is considered to be suitable for commercial-scale CO₂ storage [1,2,3], due to its favourable geological setting, its proximity to sources, and pioneering operational experience storing CO₂ at the Sleipner injection site [4]. The shallow Neogene and Quaternary sediments of the NSB form the overburden and seal to these underlying CO₂ reservoirs but are under-researched, even though the NSB is a mature petroleum system, penetrated by many thousands of wells. Quaternary sediments, up to 1000 metres thick (Figure 1), are in general bypassed to reach the deeper, profitable hydrocarbon resources.

UKCCSRC and CLIMIT programme funded scientific, governmental and industrial partners from the UK and Norway (Section 2) to collaborate with the purpose of submitting a proposal to the International Ocean Discovery Program (IODP) for scientific drilling to investigate the overburden to CO₂ storage strata.

2. The Norwegian CLIMIT funded consortium

The Norwegian national research and development programme for demonstration of Carbon Capture and Storage technology (CLIMIT) brought together Norwegian academic institutes and industrial partners to look at de-risking the development of major potential CO₂ storage reservoirs across the Central and Northern North Sea. The CLIMIT consortium worked in collaboration with the UKCCSRC partners.

3. Key outcomes

The joint consortium has sought to improve understanding of the geometry, seismic stratigraphy, and existing litho- and chrono-stratigraphy of the overburden above potential CO₂ storage reservoirs to inform this drilling proposal (Figures 2 and 3). The combined projects have reviewed existing seismic-, litho- and chrono-stratigraphic data to inform selection of the prospective sites for IODP drilling and sampling (Figure 4). It has investigated the overburden from available data, including secondary storage formations, their seal rocks and high-permeability zones, to identify gaps in our knowledge and inform selection of prospective IODP sites. The proposed drilling sites have been selected to optimise improved understanding of the connectivity between storage reservoirs, surrounding strata and Quaternary overburden, essential for the secure containment and successful implementation of CO₂ storage.

4. Research highlights

The international consortium completed the interpretation, site selection and investigation required for a scientific drilling pre-proposal which was submitted on 1st April 2014. The consortium was subsequently invited to submit a full proposal (1st April 2015). Positive feedback was received from the IODP Science Evaluation Panel and a revised proposal was submitted (1st April 2016).

The proposed scientific objectives have been presented at eight international conferences and one UKCCSRC webinar broadcast. A number of peer review publications are in progress from the research investigations.

The findings from the research investigations have improved our understanding of the strata overlying prospective CO₂ storage sites and hydrocarbon accumulations within the NSB. Also a comprehension of data needed from scientific drilling to evaluate and predict the secondary storage and containment strata with the overburden.

5. Next steps

A positive review from the IODP Science Evaluation Panel would likely result in a coring programme within the NSB that will be funded jointly between industrial partners and IODP.

References
Determination of water solubility limits in CO2 mixtures to deliver water specification levels for CO2 transportation

Principal investigator: Michael W. George  Co-Investigators: Martyn Poliakoff
Key researchers: Stéphanie Foltran

Project funded by the UKCCSRC as part of its Call 1 for Research Proposals, in partnership with the University of Nottingham
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Project Dates: May 2013 - December 2014

Project Overview

Studies of the phase behaviour and water solubility of pure and impure CO2 are of great relevance to the transport phase of the carbon capture and storage (CCS) process.

Single phase Possible corrosion
For transport through carbon steel pipelines, CO2 and any impurities present must be present as a single phase to avoid corrosion, and subsequent loss of pipeline integrity.

Procedure and Key Findings

By exploiting the high IR absorbance of H2O, the v2 bending mode absorption band of water can be monitored.

Only H2O which is present as a single phase with CO2 and any other impurities is measured, allowing observation of the changing concentration of H2O below the saturation point.

Trace impurities such as H2 and N2 have been shown to alter the phase behaviour of the CO2 at high pressure.[1]
Understanding the effect of these impurities on the solubility of H2O in CO2 is vital to confirm the safety and viability of CO2 transport through carbon steel pipelines.

Research Highlights

An integrated high pressure gas mixer and FTIR spectroscopy apparatus has been developed to facilitate these phase behaviour measurements.

Next Steps and Applications

This work has continued as part of the UKCCSRC’s Call 2 for research projects.
Similar measurements have been performed on various gas mixtures including CO2 with N2 and H2 at various percentages.
The FTIR spectroscopic method described herein has the potential to be applied to measurements of various gas mixtures and impurity concentrations, relevant to CCS and beyond, supporting the development of pipeline design standards.

References
Bio-CAP-UK: Air/oxy biomass combustion with CO₂ capture technology, UK study

Project Introduction and Background

Bio-CCS - bioenergy with carbon capture and storage - has the ability to achieve potential net negative CO₂ emissions, vital for meeting legally binding and increasingly stringent emission targets and carbon budgets. Bio-CCS has a large and distinct potential for significantly lowering CO₂ emissions from energy production; thus the key messages from this programme will have clear policy implications on decarbonisation strategies.

The Bio-CAP-UK project aims to accelerate progress towards achieving operational excellence for flexible, efficient and environmentally sustainable bio-CCS thermal power plants by developing and assessing fundamental knowledge. This is being achieved through extensive multi-scale experimental work, including bench and pilot-plant tests, combined with system simulations, techno-economic analysis and life cycle studies. The programme focuses on comparing air-firing coupled with post-combustion carbon capture to oxy-fuel combustion.

Work Package Overview

- **WP1:** fundamental studies and biomass characterisation - fuel, char and ash analysis, in terms of composition, milling, fuel ignition, combustion rate, char burnout and ash quality
- **WP2:** pilot-scale campaign - air- and oxy-firing tests, comparing biomass (white wood pellets) [see below] and Colombian El Cerrajon coal, including capture solvent degradation studies
- **WP3:** power plant simulations for air/oxy combustion - full-scale bio-CCS plant process simulations linked to CFD models of key rate-controlling components (e.g. the furnace)
- **WP4:** bio-CCS value chains in the UK - configurations for different bio-CCS options, with detailed comparisons for life cycle and techno-economic analyses

Preliminary Analysis

- Extensive analysis of fuel feedstocks and ashes are complete, including single particle combustion tests [see below]
- Devolatilisation tests show wood is more reactive, due to O₂ availability at the particle surface and increases in diffusion rate [see graph opposite]

<table>
<thead>
<tr>
<th>Oxides (%)</th>
<th>COAL</th>
<th>WOOD</th>
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<tbody>
<tr>
<td>SO₃</td>
<td>11.4</td>
<td>2.4</td>
</tr>
<tr>
<td>CaO</td>
<td>14.4</td>
<td>27.0</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>10.8</td>
<td>1.3</td>
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<td>K₂O</td>
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<td>SiO₂</td>
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<td>VOLATILES</td>
<td>37.4</td>
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<tr>
<td>ash</td>
<td>4.6</td>
<td>0.7</td>
</tr>
<tr>
<td>fixed carbon</td>
<td>58.0</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Trace Metals (mg/kg)

- Cr: 4.7 mg/kg
- Cu: 11.7 mg/kg
- Hg: 0.1 mg/kg
- Zn: 14.9 mg/kg

A new flame imaging system has been purchased for flame characterisation and assessment, along with an ellipsoidal radiometer for heat flux measurements

- The ICP-OES is ready to assess metal aerosol emissions in the flue gas, to compare to the trace levels found in the fuel and ash
- Developing predictive tools for ash deposition (slagging/fouling)
- Large-scale systems simulations completed for coal and are now being adapted for biomass modelling [right]
- Life cycle analysis indicates that oxy-firing achieves net negative CO₂ emissions at co-firing ratios of just 30wt%, but for air-firing with post-combustion capture, up to 60wt% is needed

Next steps

The new GE-designed biomass burner [right] has been manufactured and the white wood pellets are milled, ready for the pilot-scale trials in the UKCCSRC PACT 250 kW combustor [below]. Full-scale plant and systems simulations, as well as life cycle/techno-economic assessments are developing well and on schedule, utilising the fundamental data above, and will soon be validated with the experimental outputs from the combustion tests.

Reference


COAL WOOD

- 58.0 15.6
- 39.9 13.6
- 4.6 0.7
- 10.8 1.3
- 37.4 83.7
- 11.4 2.4
- 14.4 27.0
- 1.6 10.1
- 0.7 0.7
- 83.7 13.6
- 0.7 0.7
- 15.6 13.6
- 0.7 0.7
- 13.6 13.6
- 0.7 0.7
- 27.0 13.6
- 10.6 13.6
- 0.7 0.7
- 2.4 13.6
- 10.2 13.6

US white wood pellets from forestry residues

Biomass single particle ignition and combustion

The 250 kW solid fuel reactor and GE biomass/coal burner in air-firing mode with post-combustion capture, housed at the UKCCSRC PACT Core Facilities
Project overview
The project is based on the concept of CLOU (chemical looping oxygen uncoupling)

Various forms of chemical looping are possible with different degrees of integration between the oxygen release and the thermal energy production cycles.

• Most of the CLC and CLOU processes proposed thus far are conducted in a fluidised bed reactor encountering problems of contamination of the oxygen carrier and fuel leakage.

• The project has designed a hybrid form of chemical looping that achieves the optimal degree of integration of oxygen release and thermal energy production

• The need for intimate contact between the oxygen carrier and the solid fuel is also avoided.

Key findings/outcomes

Initial Sub-Stoichometric reactor operation. Commencement of reactor operation at around 350s

Successful operation of prototype – note the reduction in unburned hydrocarbon, and jump in CO₂ and O₂ concentrations.

Calcium Manganese oxygen carriers were tested over multiple cycles and low degradation rates were observed.

Use of outcomes/Avenues for exploitation/Next steps

Initial results are promising and second stage rig has been designed and constructed at Imperial.

A PhD student (funded by Imperial) is now working on the improved prototype rig.

The process is being patented, which is why little detail is shown here.

The pilot facilities which were commissioned at Cranfield continue to be used for tests in a number of different areas.
Project overview

A potential bottle-neck for CCS is the transport of CO₂ from power plants to the storage location, by pipeline. Key to safe and inexpensive transport is a detailed understanding of the physical properties of carbon dioxide. However, no gas separation process is 100% efficient, and the resulting carbon dioxide contains a number of different impurities. These impurities can greatly influence the physical properties of the fluid compared to pure CO₂. They have important design, safety and cost implications for the compression and transport of carbon dioxide. This project aimed to develop new methods to produce custom models (equations of state) for impure CO₂ behaviour for CCS.

Key findings

Algorithms: We have applied a range of cutting-edge algorithms to characterise the parameter behaviour in comparison to experimental data. Once the user has defined the equation of state and mixing rules, our algorithms locates the ‘best-fit’ parameters. The algorithms also determine the degree of certainty with which the experiments determine the model parameters and this, ultimately, provides the uncertainty in model predictions. We have developed two algorithms: a Markov Chain Monte Carlo (MCMC) approach; and a parallel tempering algorithm which improves the speed and ability to find good parameter values.

Results: We have used our algorithms to develop a new equation of state for CCS modelling [1]. This equation of state produces agreement to CCS relevant data that is superior to the industry-standard GERG model (see fig 2).

Research highlights

This project focused on developing equations of state for CO₂ mixtures in CCS applications. Our new approach enables end-users to build new equations of state that are customised to their needs. Our fitting algorithms rapidly and effectively locate parameter values that accurately fit experimental measurements. The methods quantify the uncertainty in the model's predictions due to experimental errors, incomplete measurements and model imperfection. We have produced a user-friendly graphical interface for our software that allows user to build and evaluate new customised equations of state (see fig 1).

Avenues for exploitation and next steps

In May 2014 we hosted a software workshop at Nottingham, which had 13 attendees (10 from industry and 3 academics). The workshop had interactive training on our techniques and software. We also sought feedback and suggestions for future development from the workshop attendees.

We are currently working with computational fluid dynamics modellers to implement our equation of state in a model for a pipeline rupture event.

References

Oxyfuel and exhaust gas recirculation processes in gas turbine combustion for improved carbon capture performance

Principal investigator: R Marsh Co-Investigators: P Bowen, A Valera-Medina
Key researchers: S Morris, A Giles, D Pugh, J Runyon
Project funded by the UKCCSRC as part of its Call 1 for Research Proposals, in partnership with Cardiff University
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Project overview
This research is concerned with oxyfuel combustion in gas turbine applications, in particular concentrating on the use of modern swirl-stabilised burners. Oxyfuel is considered a particularly challenging idea, since the resultant burning velocity and flame temperatures will be significantly higher than what might be deemed as a practical or workable technology. For this reason it is widely accepted that EGR-derived CO2 will be used as a diluent and moderator for the reaction (in essence replacing the role of atmospheric nitrogen).

The key challenges in developing oxyfuel gas turbine technology are therefore:
• Flame stability at high temperatures and burning rates.
• The use of CO2 as a combustion diluent.
• Potential for CO emission into the capture plant.
• Wide or variable operating envelopes across diluent concentrations.
• Differences in the properties of N2 and CO2 giving rise to previously unmeasured flame heat release locations.

Research highlights
The differences between N2 and CO2 as swirl combustion diluents (shown below) demonstrate the shift in heat release location. This is the first time this has been accurately compared. These findings have been presented in the gas turbine (ASME 2014, 2015) and combustion communities (Combustion Institute 2016).

Key findings
• The presence of high concentrations of oxygen does not significantly affect the operational envelope of the burner in terms of molar flow rate.
• It has been possible to operate the swirl burner with high O2 concentrations at elevated pressure.
• The presence of CO2 in the reactants causes a reduction in the burning velocity of the mixture and acts as a greater heat sink than atmospheric N2.
• It was possible to run the burner at stoichiometric levels of air and methane when CO2 was used as a diluent.
• There is strong evidence to suggest that (diluent) CO2 cools the flame, leading to the production of CO in the exhaust, rather than thermally dissociating into CO as previously thought.

Use of outcomes and subsequent research steps
Gas turbine developers and researchers can take the findings in order to develop burners for use in CCS-oxyfuel gas turbine power generation systems. The results can now also be used by modellers examining the effects of CO2 as a combustion moderator in the simulation of future CCS-compatible gas turbine engines. This will allow for the validation of computational systems, which can be used to simulate the effects of oxyfuel and exhaust gas recycling on gas turbine power systems.

This research has shown the genuine potential for the use of modern DLE swirl burner technology with oxyfuel and EGR technologies. The next step is to intensify and consider scale-up for this technology. As a result of this, a £1.1M grant has been secured from EPSRC to examine selective EGR (the SELECT project, reference EP/M001482/1).
Project overview

Injection of fluids into geological formations induces microseismic events due to pressure changes causing either opening mode or shear mode fracturing. Injection for CO\textsubscript{2} storage is designed to be well below the pressures required for hydraulic fracturing. Due to the inherent heterogeneity of geological formations, some existing structures will be critically stressed so small microseismic events are inevitable. Current reservoir monitoring strategies either examine time-lapse variations in the rock’s elastic properties (4D seismic) over diffuse areas, or aim to detect leakage from diffuse and point sources at the seabed (e.g. the QICS project).

The aim of the project is twofold:

- test the potential of a new technology (nanoseisms) for passive seismic monitoring that aims to image focused flow pathways at depth of an active CO\textsubscript{2} injection site: the Aquistore site, Canada
- use a multi-disciplinary approach to interpret passive seismic data sets obtained during operation of the same site.

Research highlights

Analysis to-date has focused on the determination of the spectral characteristics of the records (see Figure 1). The short-period nanoseismic array of the University of Strathclyde was recording continuously for 56 days at a sampling rate of 1000Hz. During this time period, CO\textsubscript{2} injection took place for the 60% of the time.

Emerging findings

Spectral analysis of downsampled (250Hz) recordings shows differences in the frequency content of hours falling within the CO\textsubscript{2} injection period compared to those at intervals when injection had stopped. In depth analysis of the recordings where these differences have been found is ongoing to determine the causes, e.g. Figure 2.

Next steps

Interpretation of results obtained from the analysis of the seismic data will be based on the combination of independent data sets, e.g. geological information (Figure 3). Our outcomes can provide important information on preferential flow pathways within the storage complex and the overburden that can be used to inform inject and monitoring strategies at the Aquistore site. The data collection and subsequent analyses will also provide a valuable benchmark for monitoring strategies that could be applied to future storage sites.