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Energy Procedia 63 (2014) 504 – 510

Energy Procedia

GHGT-12

OxyCAP UK: Oxyfuel Combustion - Academic Programme for the UK

H. Chalmers[c], M. Al-Jeboori[d], B. Anthony[b], S. Balusamy[a], S. Black[f], F. Cavallo Marincola[d], A. Clements[f], H. Darabkhani[b], J. Dennis[a], T. Farrow[g], P. Fennell[d], B. Franchetti[d], L. Gao[e], J. Gibbins[c], S. Hochgreb[a], M. Hossain[e], N. Jurado[b], A. Kempf[d,h], H. Liu[g], G. Lu[e], L. Ma[f], S. Navarro-Martinez[d], W. Nimmo[f], J. Oakey[b], A. Pranzitelli[f], S. Scott[a], C. Snape[g], C-G. Sun[g], D. Sun[e], J. Szuhánszki[f], I. Trabadela[c], F. Wigley[d], Y. Yan[e], M. Pourkashanian[f]*

[a]*University of Cambridge, Cambridge, UK*
[b]*Cranfield University, Cranfield, Bedford, UK*
[c]*University of Edinburgh, Edinburgh, UK*
[d]*Imperial College London, London, UK*
[e]*University of Kent, Canterbury, Kent, UK*
[f]*University of Leeds, Leeds, UK*
[g]*Univerity of Nottingham, Nottingham, UK*
[h]*Universität Duisberg-Essen, Germany*

Abstract

The OxyCAP-UK (Oxyfuel Combustion - Academic Programme for the UK) programme was a £2M collaboration involving researchers from seven UK universities, supported by E.On and the Engineering and Physical Sciences Research Council. The programme, which ran from November 2009 to July 2014, has successfully completed a broad range of activities related to development of oxyfuel power plants. This paper provides an overview of key findings arising from the programme. It covers development of UK research pilot test facilities for oxyfuel applications; 2-D and 3-D flame imaging systems for monitoring, analysis and diagnostics; fuel characterisation of biomass and coal for oxyfuel combustion applications; ash transformation/deposition in oxyfuel combustion systems; materials and corrosion in oxyfuel combustion systems; and development of advanced simulation based on CFD modelling.

Peer-review under responsibility of the Organizing Committee of GHGT-12

* Corresponding author. Tel.: +44-113-343-2512; fax: +44-113-246-7310.
E-mail address: m.pourkashanian@leeds.ac.uk

Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.055

Selection and peer-review under responsibility of GHGT.

Keywords: oxycombusion; oxyfuel; CFD; flame imaging; fuel characterisation; materials; ash deposition

1. Introduction

Oxyfuel combustion of coal appears to offer costs and performance that are at least as competitive as other CO_2 capture technology options. In addition, the specific technical characteristics of oxyfuel combustion are likely to offer advantages in certain important applications. For example, oxyfuel technology has significant potential to provide an effective CO_2 capture solution for sites with water constraints and will probably also be useful to improve utilization of some difficult coals.

Although the core oxyfuel concept is not new, there is a need to continue to develop both the underpinning science and associated scientific capacity needed to support successful widespread commercialisation of oxyfuel power plants. The OxyCAP-UK (Oxyfuel Combustion – Academic Programme for the UK) programme was a £2M collaboration involving researchers from seven UK universities, supported by E.On and the Engineering and Physical Sciences Research Council. The programme ran from November 2009 to July 2014 and developed underpinning academic research capability for oxyfuel combustion in four key, interlinked areas:

- New experimental techniques for oxyfuel combustion;
- Advanced computer modelling techniques required for analysis of oxyfuel combustion plant;
- Experimental data on coal ash and boiler material behaviour under oxyfuel conditions; and
- Training and development of new researchers in the field.

The remainder of this paper will outline the key scientific findings from the OxyCAP-UK programme. In particular, it will:

- Highlight the importance of developing state-of-the-art research pilot test facilities;
- Demonstrate the successful use of 2-D and 3-D flame imaging systems for monitoring, analysis and diagnostics;
- Provide an overview of work undertaken on fundamental aspects of oxyfuel combustion systems (fuel characterization, ash transformation/deposition and materials and corrosion in oxyfuel combustion systems); and
- Introduces the development and use of advanced simulation based on CFD modelling within the OxyCAP-UK programme.

2. Development of UK research pilot test facilities for oxyfuel applications

The OxyCAP-UK project has developed a 250 kW Combustion Test Facility (CTF), which is now part of the UK CCS Research Centre PACT (Pilot-scale Advanced Capture Technology) facilities [1]. This facility has been used to generate a comprehensive database for oxy combustion under various test conditions, providing much needed validation data for CFD submodels. The CTF can fire gas, coal, or coal/biomass blends as fuel and the oxidising medium can be either air, a synthetic mixture of CO_2/O_2 with or without steam injection, or a mixture of wet recycle gas and O_2. The facility can also supply flue gas to the connected post combustion carbon capture plant for solvent testing and development.

The experimental programme has included baseline studies under both air- and oxy-firing (21%) conditions. Further parametric studies were also carried out under simulated oxyfuel conditions with recycle ratios set to give O_2 concentrations of 27%, 30% and 33%. Experimental campaigns included a number of conventional measurements (temperature using suction pyrometry, in-furnace heat flux profiles, species profiles for $O_2/CO/CO_2/SO_2/NO_x$, unburnt carbon and ash analysis). Additionally, advanced visualization using 2-D and 3-D flame imaging was also carried out and this is discussed further below.

Work has also been undertaken using a 100kWth coal/biomass rig at Cranfield University that is also part of the UKCCSRC PACT facilities. The main activities based on these facilities have been experimental trials in a 100kW retrofitted oxy-combustor, and developing a kinetic model using Aspen Plus that predicts gas composition and temperatures of the process when varying the main operational parameters [2]. For the experimental part of the project, primary parameters such as type of fuel (coal/biomass/coal-biomass blends), percentage of recycle flue gas, and type of recycle flue gas (dry/wet) were varied to analyse their effects on the outputs of the process (gas composition, temperatures reached, and composition of ash generated). Additional aspects like sulphur trioxide (SO_3) levels inside the combustor, heat transfer, and study of the process using a dry recycle flue gas, have also been studied. In parallel, a kinetic simulation model has been designed to study the oxy-combustion process through the co-firing of coal and biomass blends.

An important feature of the work with the Cranfield rig has been a retrofit to existing facilities to allow an additional suite of measurements including SO_3 measurement by controlled condensation method and additional sampling for gas chromatography using FTIR. The experimental programme suggests that heat fluxes can be around 3 times higher in oxy-firing conditions than in air-firing conditions. It also suggests that heat fluxes associated with coal combustion are around 1.4 times higher than those associated with a cereal co-product biomass.

3. 2-D and 3-D imaging systems for monitoring, analysis and diagnostics

Within the OxyCAP-UK project, two-dimensional (2-D) and three-dimensional (3-D) flame imaging systems have been developed to quantify the fundamental physical characteristics of oxyfuel flames. The systems are capable of measuring a range of flame characteristics, including length, surface area, volume, temperature distribution, soot concentration and emissivity as well as intensities of flame radicals. Photodiodes are incorporated in the 2-D imaging system to measure the oscillation frequency and stability of the flame. These techniques provide digital images and videos of the flame as well as computer tomographic reconstruction of the flame in 3-D [3]. As noted above, experimental work has been undertaken on the 250 kW solid fuel combustion test facility to assess the performance and operability of the systems (see also Fig. 1). Measurements include:

- in-flame temperature profiles using suction pyrometry;
- heat flux profiles using an ellipsoidal radiometer and total heat flux probes;
- in-flame and exhaust species profiles;
- flame characteristics, including shape, luminosity, temperature, soot concentration and oscillation frequency;
- intensities of flame radicals;
- flame stability index;
- velocity profiles within the top section of the furnace (for both non-reactive and reactive cases); and
- coal burnout and ash characterisation.

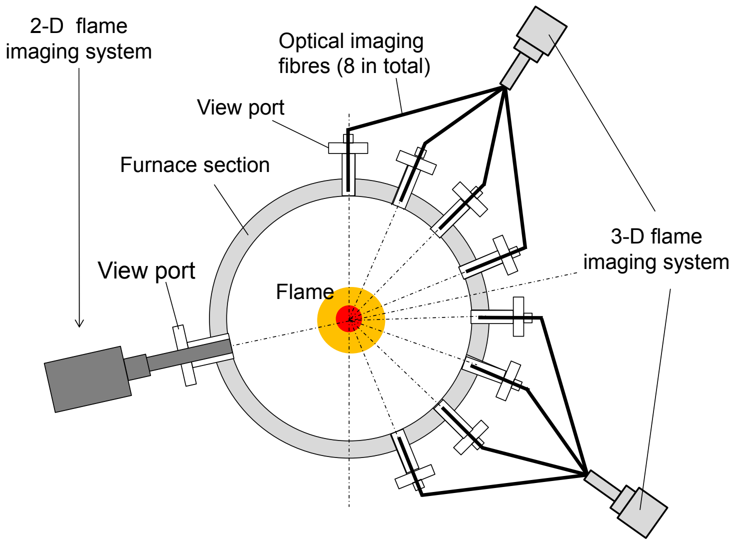

Fig. 1. Schematic of the 2-D and 3-D flame imaging system deployed at the UK CCS Research Centre core facilities.

Additionally, a novel instrumentation system for measuring velocity, concentration and particle size distribution of pulverised fuel flow has been developed. The system operates on electrostatic and piezoelectric sensors and signal processing algorithms [4]. It has been evaluated on a coal/biomass flow test rig at Kent and on a biomass flow pipeline at Tilbury Power Station.

The project has also developed improved capability to use laser diagnostic techniques to make flow field measurements under oxyfuel conditions building on previous experience at the University of Cambridge. This work found that optical diagnostics can be usefully employed in obtaining velocities in coal-laden flames, with coal as the seeding particle. Laser Doppler anemometry (LDA) provides time and space resolved measurements with 1 mm spatial resolution, whilst particle image velocimetry (PIV) requires fast shuttering to reject the high luminosity of flames. A database of velocity, OH PLIF and LII in turbulent flame measurements is now available for different coal loadings, O_2 and CO_2/N_2 ratios [5]. The data will be used for validation of CFD codes, with requests received from Japan and Germany as part of a new workshop initiative for coal oxyfuel combustion modelling. The measurements show that O_2 content must be increased from 21% to 30-40% to achieve similar reactivity in oxyfuel firing conditions.

4. Fundamental aspects of oxyfuel combustion systems

A broad range of activities have been undertaken within the OxyCAP-UK programme to improve knowledge and understanding in key underpinning science relevant to oxyfuel combustion systems. This work has included fuel characterization using a drop tube furnace (DTF) and a purpose-built ignition chamber, analysis of ash transformation and deposition in oxyfuel environments and also developments in understanding of materials and corrosion that are relevant for design and operation of oxycombustion systems.

The impact of CO_2 and steam on devolatilisation and char burn-out in relation to normal air firing has been assessed by a comprehensive DTF programme at the University of Nottingham. The DTF operates up to 1450°C which is high enough to achieve the maximum volatile matter yields for coals with relatively short residence times. The key findings from this experimental programme are:

- Significantly higher yields of volatiles were obtained for all coal samples examined when devolatilisation occurred in CO_2 at higher temperatures above 1100°C and residence time 200 ms;
- With the presence of steam, the combinative effect of CO_2-char and steam-char gasification reactions led to even higher yields of volatiles being produced in oxy-fuel conditions;
- For devolatilisation in both N_2 and CO_2, the amount of nitrogen released into volatiles is proportional to the yields of volatiles being produced. However, when devolatilisation occurred in CO_2 or CO_2/steam, the higher yields of volatiles led to significantly higher proportions of fuel nitrogen being released;
- The impact of CO_2 on char burnout varied significantly with different coals; and
- Biomass co-firing can improve char combustion performance in both air and oxy-fuel firing conditions, and the effect is significantly more pronounced in oxy-combustion [6].

Researchers at the University of Cambridge have also carried out fundamental work to quantify the effect of gasification on rates of char combustion in fluidised beds for highly reactive chars. This work provides increased understanding of interactions between mass transfer and gasification in fluidised bed conditions, which will benefit the development of associated models.

Additionally, dust ignition tests in oxyfuel atmospheres have been carried out at the University of Edinburgh using a purpose built ignition chamber. Fundamental data on ignition under oxyfuel conditions has been gathered for a range of coal and biomass types leading to improved understanding of acceptable O_2 levels in the flue gas recycle. For example, for the series of experiments carried out within the OxyCAP programme a relatively stronger ignition source was required for the biomass samples tested when compared with pulverised coals previously tested. This is tentatively attributed to larger particle sizes and higher moisture contents [7]. Insights from this work are expected to improve mill safety in oxyfuel conditions as well as providing fundamental data for combustion modellers.

Ash transformation and deposition in oxyfuel environments has been explored in a programme of work led by Imperial College London, which has characterised samples generated by pilot scale tests undertaken by other

OxyCAP-UK partners. Analysis of ashes was conducted using scanning electron microscopy (SEM). Analysis of sample microstructure for samples fired pilot scale under oxyfuel conditions (26% enrichment and 2, 3 and 4% excess O_2) showed that:

- The morphology of the particles changed from highly distributed spherical shapes to agglomerates of fine particles;
- The shape of particles changed from mainly spherical to plate like shapes and mottled surface textures; and
- For two of the coals tested particle sizes are significantly lower for oxyfuel particles, but for a third coal similar particle sizes are observed.

Additionally, comparison of air- and oxy-firing trials indicate that the phases (examined by XRD) are closely comparable, which means the cement industry can take ashes from either source. Further work to examine whether carbonates might persist in oxy-firing conditions could be considered. The analysis in this study suggested that Ca may be more leachable from air-fired ashes (more CaO, less $CaCO_3$), but fresher ash samples should be used to verify this tentative conclusion.

Finally, Cranfield University have carried out combustion rig trials under a range of oxy-fuel combustion conditions to support a series of laboratory corrosion and trace element speciation tests, which have generated new data required for the development of predictive corrosion rate and trace element distribution models. The corrosion performance of materials in a wide range of gaseous/deposition environments simulating industrial process conditions has been considered. In particular, different fuels, a range of operational conditions and the practicality of changes in fuel quality under different oxygen percentages, relevant for both pulverised fuel and pressurised fluidised bed combustion, have been assessed in order to define the operation envelope.

The experimental programme at Cranfield has also suggested no major difference between air- and oxy-firing ash deposits for the range of test conditions explored (except for an expected increase in levels of sulphur compounds that is typically expected with recycled flue gas). The deposit compositions broadly follow conventional understanding of expected influence of fuel properties on deposition, although further work with a broader range of fuels (particularly different biomasses) is needed.

5. Development of advanced simulation based on CFD modelling

CFD (computational fluid dynamics) simulations have been performed in ANSYS FLUENT using RANS and LES. The priorities for advanced simulation within the OxyCAP-UK programme were determined in consultation with industry, which included discussing key concerns over availability of physical models for CFD simulation and the expected impact of models of CFD simulation accuracy with several industrialists. The key findings of this consultation are shown in Fig 2. A particular focus of the OxyCAP-UK programme was, therefore, in developing new CFD submodels including radiation and char gasification reactions. Other techniques such as flicker analysis were also progressed [8]. Validation and improvements to new and existing models have been completed, with model development including the incorporation of the full spectrum correlated k-method (FSCK) and Mie theory for spectral radiation in CFD.

The CFD modelling team provided support to experimental groups participating in the OxyCAP-UK programme and used data from these groups to validate models. They also carried out simulation studies on full-scale power plants to improve understanding of oxyfuel power plant performance. For example, Black et al [9] used CFD as a predictive tool to examine the effects of firing under air–biomass, oxy-coal and oxy-biomass conditions in comparison to an air-coal baseline. Oxygen concentrations of 25% and 30% (by volume) with a wet flue gas recycle were considered. The results suggested reduced radiative heat transfer to the radiative sections of the boiler and increased carbon in ash when firing biomass, which was attributed to the relatively large size of biomass particles. This work also suggested that that the optimum oxygen concentration for heat transfer to be closely matched with air-coal, lies between 25% and 30%, but for oxy-biomass firing a value greater than 30% may be needed.

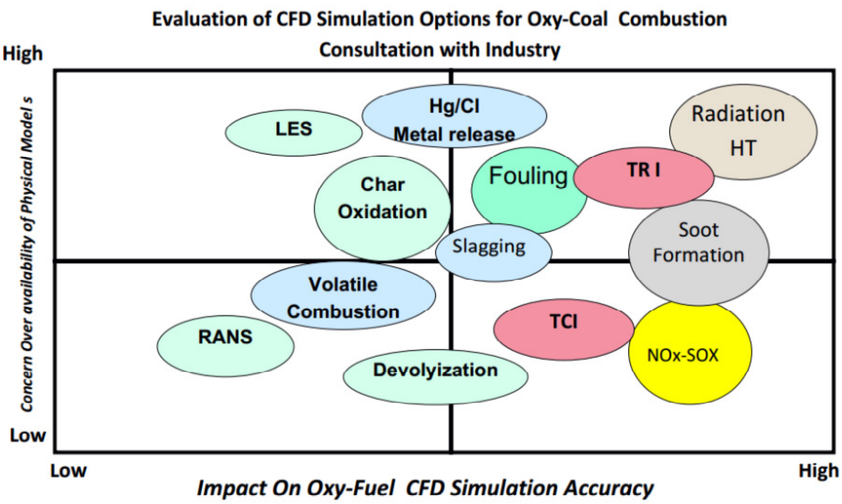

Fig. 2. Overview of outcomes from consultation with industry on oxy-coal combustion CFD sub-model priorities

In addition to effective use of ANSYS, the Oxy-CAP programme has also included work to develop improved Large Eddy Simulation (LES) as an effective approach to simulation of turbulent combustion of coal [10-12]. In particular, it is expected that these approaches can provide improved representation of the interaction between turbulence and combustion. In LES, closure models are used only for the smallest scales with equations retained in the model and solved for larger scales. Although this approach is more computationally expensive, it is able to provide improved predictive capability since an accurate description of turbulent flow is used. This allows unsteady analysis to be undertaken and extreme events to be observed.

6. Conclusions

This paper has provided an overview of the OxyCAP-UK programme. Overall, the programme has progressed state-of-the-art understanding in a number of areas that are important for effective development and deployment of oxyfuel power plants. Improved systems for flame imaging and flame diagnostics have been developed and tested under realistic conditions. Advanced CFD-based simulation techniques have also been progressed, including development of key sub-models identified as priorities in consultation with relevant industrialists and advances in Large Eddy Simulation for turbulent combustion of coal. These activities have been complemented by a substantial body of work on fundamental aspects of oxycombustion systems including fuel characterization using a drop tube furnace (DTF) and a purpose-built ignition chamber, analysis of ash transformation and deposition in oxyfuel environments and also developments in understanding of materials and corrosion that are relevant for design and operation of oxycombustion systems. A further achievement of the programme has been substantial developments in infrastructure and capacity, including combustion test facilities that have now been incorporated into the UK CCS Research Centre PACT facilities (www.pact.ac.uk).

Acknowledgements

The authors gratefully acknowledge financial support from E.On and Engineering Physical Sciences Research Council through grant EP/G062153/1.

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