Institution: Imperial College London

Unit of Assessment: 13B Metallurgy and Materials

Title of case study: Reductions in emissions and improvements in boiler efficiency at power stations burning coal and biomass

1. Summary of the impact

Two related research activities 1) on low NOx burners and 2) on co-firing of biomass have led to combined economic savings estimated to be in the region £40M-£70Mpa.

The fitting of low NOx burners to power station boilers reduced the NOx emissions but resulted in a reduced amount of saleable bottom slag and a finer pulverised fuel ash (pfa), which placed an increased load on the electrostatic precipitators. Additions of pfa to the power station coals were found to increase the overall combustion efficiency, while at the same time providing an increased amount of a saleable boiler slag and a pfa that could be used as a cement replacement material.

Despite the very different nature of the ashes produced from the combustion of biomass and coals, a detailed characterisation of the residues demonstrated that, with an appropriate choice of both biomass type and coal, a successful co-firing at up to 50% of coal replacement with biomass was possible. Co-combustion with increased levels of coal replacement has produced significant reductions in power station emissions, resulting in both environmental and economic benefits.

2. Underpinning research

Privatisation of the coal and power industries released the electricity generators from contracts that had tied them to the purchase of UK coals. The coal-fired power stations had been designed and built for the CEGB to burn just UK coals. A research group, led by Professor Jim Williamson, in the Department of Materials, had for some years been characterising UK coals, mineral matter, ashes and slags to provide the basis for improvements in the methods used for predicting the slagging and fouling propensity of the coals. It should be noted that the cost of lost power generation and maintenance for each unscheduled boiler outage that occurs as a result of fouling, was several million pounds.

The ability of the generators to purchase overseas coals was seen by the power companies as a way of reducing, or at least stabilising, UK electricity prices. However, many of the world traded coals were of a very different nature to the UK coals, and lacked essential data on combustion behaviour. Imperial College London, with the backing of industry, agreed to an increased research activity that would assist the power companies with the choice of new coals, provide data on combustion behaviour, gaseous and solid emissions and predictions for boiler performance.

Research groups established in the Departments of Materials, Mechanical and Chemical Engineering, achieved international recognition, and with this, came substantial new funding from the power companies, EPSRC, EPRI and the European Coal and Steel Research Fund. In the Department of Materials, a 1600°C entrained flow reactor (EFR) was designed and built (Ian Hutchings, October 1993) to provide a facility that would simulate the time and temperature conditions experienced by coal particles in a full-sized, pulverised, coal-fired boiler. The reactor provided combustion products that were characterised using computer controlled scanning electron microscopy (CCSEM)(Fraser Wigley, since February 1993) and techniques were developed to characterise the complex nature of the coal mineral distributions and the nature of the combustion products (1). The facilities enabled key combustion parameters to be established using the relatively small quantities of overseas coals that were on offer (2). Coal research in the Department of Materials concentrated on some of the major issues that were confronting the power generation industry. These included improved techniques for predicting the slagging and fouling propensity of a coal ash (3)(Fraser Wigley, Nick Manton, Nigel Russell, since 1990), prediction of NOx emissions (Fraser Wigley and Jim Williamson, 1998-2002), the effects on ash slagging using blended coals, the origins of the unburned carbon in ash, the fate of trace elements in a coal on combustion and gasification (Fraser Wigley, Andy Bushell, 1995-2000), predicting the erosive and abrasive properties of a pulverised coal (4)(Jon Wells, 2002-2004), the characterisation of biomasses and the interactions of a co-fired biomass ash with a coal ash (5)(Fraser Wigley, 2001-2008).

Underpinning science leading to two key impacts

The results of these studies enabled the power generators to meet restrictions on gaseous emissions, the targets set for CO_2 reductions and to increase the proportion of electricity generated from renewable sources. Improvements in boiler performance provided savings to the industry (and consumers) estimated at millions of pounds. Two projects described below have been chosen to illustrate the impact that these studies had on power station performance.

1 Low NOx Burners Savings of ~£1Mpa

The retrofitting of low NOx burners reduced the NOx emissions but produced

(a) an ash with a higher carbon content,

(b) reduced amounts of saleable bottom slag, and

(c) a pfa with a finer particle size that placed an increased load on the electrostatic precipitators.

Studies showed that the lower flame temperatures produced by low NOx burners produced ash particles that were less sticky, with a reduced tendency to agglomerate. The initial combustion conditions being less oxidising reduced the conditions required for a high carbon burnout, with the boiler now requiring more coal to provide the same thermal out-put. An initial programme of mineral and pfa additions to a coal made use of the EFR, providing deposits, combustion and cyclone ashes, each of which was subjected to detailed chemical and microstructural characterisation (6). The initial success of the project was followed with trials using the RWE 0.5 MW combustion test facility (CTF) which allowed an increased range of flame characteristics and boiler conditions to be monitored. The success of the CTF trials then lead to a full-scale boiler implementation of pfa additions to a coal at an RWE npower power station using a 600 MW boiler.

2 Use of Biomass – savings of ~£40M-£70M pa

Combustion of biomass is considered to be an essentially CO_2-neutral process, but biomass combustion alone has an efficiency limited to ~35%, when co-fired with coal at higher temperatures, the efficiency rises to 43%. However, the effects of the inorganic components of biomass on boiler ash behaviour was of major concern since the alkalis present in a biomass, namely high levels of CaO, MgO, K_2O, Na_2O and P_2O_5, can significantly reduce the viscosity of the coal ash producing sticky ash particles with enhanced deposition rates and changes to both ash slagging and fouling behaviour. Power generators had therefore proceeded with much caution concerning the amount of coal to be replaced by biomass, limiting replacement to 5 to 10 wt% of the coal for fear of producing intractable slags and fouling deposits. The aims of a study funded by the DTI under the New and Renewable Energy Programme, with additional support from Mitsui Babcock, E.ON and RWE npower, were to establish the upper limit of coal replacement before serious slagging and fouling problems occurred. The studies at Imperial College London made use of the EFR, used a variety of UK and imported coals, with five biomass types, namely miscanthus, olive waste, sawdust, cereal straws and switch grass. Biomass additions to the coal ranged from 5 to 40 wt% of the coal ash. Ash and deposits were subjected to detailed microstructural, studies, chemical analysis and calculated ash viscosities. Ash deposition rates were determined from the proportion of ash retained on deposition probes.

3. References to the research * References that best indicate quality of underpinning research.

1. * Wigley, F., Williamson, J., Gibb, W.H. “The distribution of mineral matter in pulverised coal particles in relation to burnout behaviour”, *Fuel*, **76**, 1283-1288, 1997. http://dx.doi.org/10.1016/S0016-2361(97)00139-7

2. Gibbins, J.R., Williamson, J. “Advances in laboratory tests for predicting coal-related combustion problems”, *Power and Energy*, I Mech E, **212**, Part A, 13-26, 1998. doi: http://dx.doi.org/10.1243/0957650981536709

3. * Russell, N.V., Wigley, F., Williamson, J. “The roles of lime and iron oxide on the formation

of ash and deposits in PF combustion", *Fuel*, **81**, (5), 673-681, 2002. http://dx.doi.org/10.1016/S0016-2361(01)00154-5

4. Wells, J.J., Wigley, F., Foster, D.J., Livingston, W.R., Gibb, W.H., Williamson, J. "The nature of mineral matter in a coal and the effects on erosive and abrasive behaviour", *Journal of Fuel Processing Technology*, **86**, 535-550, 2005. http://dx.doi.org/10.1016/j.fuproc.2004.04.002

5. *Wigley, F., Williamson, J., Malmgren, A., Riley, G.S. "Ash deposition at higher levels of coal replacement by biomass", *Journal of Fuel Processing Technology*, **88**, 1148-1154, 2007 http://dx.doi.org/10.1016/j.fuproc.2007.06.015

6. Wigley, F., Williamson, J., Riley, G.S. "The effect of mineral additions on coal ash deposition", *Journal of Fuel Processing Technology*, **88**, 1010 -1016, 2007 http://dx.doi.org/10.1016/j.fuproc.2007.06.008

4. Details of the impact

Low NOx Burners Savings of ~£1Mpa

Unburned carbon in power station ash represents a loss in combustion efficiency, but this is mitigated by electrostatic separation of pulverised fuel ash (pfa) into ash fractions with low and high carbon. This enables the low carbon pfa to be marketed as a cement replacement material, while the pfa fractions with higher carbon contents provided ashes containing sufficient carbon for them to be used as a low cost fuel. The research programme and subsequent boiler trials showed that addition of pfa to a coal not only produced no undesirable boiler effects, but in fact increased the overall combustion efficiency and provided increased amounts of a saleable slag and pfa. The benefits from the ash refiring programme may be summarised as providing:

- an increased amount of a bottom slag for sale.
- an increase in pulverised fuel ash (pfa) sales.
- a reduction in payments of landfill tax with less ash to dispose of
- a techno-economic assessment by an independent consultant [A] of pfa additions to the coal determined savings of **~£1 M** pa for a typical 2000 MWe pulverised coal-fired boiler.

Biomass additions Savings of ~£40-60M pa

It was shown that with an appropriate choice of biomass and coal, the viscosity of the co-fired ash that could be maintained at a level above which slagging and fouling in a boiler could be avoided, even at 50% replacement levels. The findings at Imperial College London were then followed with pilot scale trials using the RWE npower 0.5 MW combustion test facility at Tilbury (CTF). This allowed an increased range of boiler conditions and flame characteristics to be monitored. At this stage a cautious economic assessment of biomass co-firing was made. This showed that substantial financial benefits could be achieved by a power generator, including the resale value of the carbon credits, the value of the renewable obligation certificates (ROCs) and the levy exempt certificates (LECs), even when the added cost of biomass transportation and storage were included. Estimates made were based on a power station output of 2000 MWh_e operating at a load factor of 70%, and with either a 20% or 50% thermal replacement of the coal with a biomass. The cost of modifications to the storage facilities, transportation and milling of the biomass would depend on the amount of biomass to be co-fired. Reductions in fuel costs when biomass replaced coal (£70 per tonne for coal) and reductions in Landfill Tax for ash disposal (£6.5 per tonne) all resulting in a substantial economic benefit with

- at 20% thermal replacement of coal, net income would be **£40 - 70M**pa [B]
- at a 50% thermal replacement, net income could rise to **£110M**pa [B]

The current UK situation is close to the **20%** replacement scenario described above. The research programme provided the power generators with confidence to significantly increase the amount of biomass being co-fired at UK power stations. [C,D]

A Corporate Engineer for Fuels and Combustion, RWE npower of RWE notes that: *"The high biomass project studied the impact of high level of biomass co-firing. This project was one of the underpinning studies into high biomass burn that lead to the decision to convert Tilbury biomass to 100% biomass firing. The reduction in CO_2 emissions is massive and it has led the industry as a whole to look at unit conversions as a viable option for old coal fired power stations."* [C]

The trials at Tilbury did indeed encourage the industry to implement the use of the process and in July 2012 Drax Power Ltd announced that it would transform itself into a mainly biomass-fueled energy generator, and is now converting three of its six generating units. The Tilbury Biomass experiment demonstrated the viability and the experiment at Tilbury has now ended, pending the outcome of Government decisions regarding new energy contracts to be announced in 2014.

The situation regarding the production of biomass boilers is extremely encouraging and business is buoyant. The Group Leader Fuels and Chemistry at Doosan Power Systems noted that:

"*The work has been instrumental in the development of advanced boiler and burner design methods, in the development of biomass firing and co-firing technologies and in the development of oxyfuel firing technologies for CO_2 capture from coal-fired power station boilers."* [E]

Doosan Power Systems has successfully secured a $170M contract for the conversion of a 227MWe lignite fired boiler to 100% biomass at the Atikokan Generating Station, Ontario. [F]

Finally, the research at Imperial contributed towards the view expressed in the UK Renewable Energy Roadmap published by DECC in 2011 [G] that electricity produced by sustainable biomass could provide a third or more of the required renewable power by 2020 (some 32050TWh per year).

5 .Sources to corroborate the impact

[A] Assessment of Ash Re-firing and Mineral Addition – Impact on Plant Performance and Ash Disposal Report No. COAL R296 DTI/Pub URN 05/1684 (2005) http://ukerc.rl.ac.uk/pdf/DTICC325_file28526.pdf. Also available here.

[B] Internal RWE Confidential report available entitled "High burn biomass - Economic Assessment" written by Alf Malmgren et al., August 2008. Available on request.

[C] Corporate Engineer for Fuels and Combustion, RWE npower. Letter dated 26 March 2013 to confirm substantial economic benefit from the research to the company

[D] http://www.rwe.com/web/cms/en/1295424/rwe-npower/about-us/our-businesses/power-generation/tilbury/tilbury-biomass-conversion/ *(Archived at https://www.imperial.ac.uk/ref/webarchive/zvf)*

[E] Letter from Group Leader Fuels and Chemistry, Doosan Power Systems dated 17th April 2013.

[F] http://www.doosanpowersystems.com/NewsEvents/News/2012-09-28/Doosan-Power-Systems-secures-biomass-conversion-contract-with-Ontario-Power-Generation/ *(Archived at https://www.imperial.ac.uk/ref/webarchive/1vf)*

[G] UK Renewable Energy Roadmap, Department of Energy and Climate Change, 2011 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48128/2167-uk-renewable-energy-roadmap.pdf. Archived here on 28/10/2013