This is a repository copy of *Biomass fuel flexibility in future conventional power generation*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/101335/

Version: Accepted Version

Proceedings Paper:

Mason, PE, Riaza, J, Chalmers, H et al. (3 more authors) (2016) Biomass fuel flexibility in future conventional power generation. In: 5th IET International Conference on Renewable Power Generation. RPG 2016, 21-23 Sep 2016, London, UK. Institution of Engineering and Technology (IET) . ISBN 978-1-78561-301-2

https://doi.org/10.1049/cp.2016.0559

This paper is a postprint of a paper submitted to and accepted for publication in IET Renewable Power Generation and is subject to Institution of Engineering and Technology Copyright. The copy of record is available at IET Digital Library.

Reuse
Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Biomass fuel flexibility in future conventional power generation

P. E. Mason*, J. Riaza†, H. Chalmers†, L.I. Darvell*, J. M. Jones*, A. Williams*

* School of Chemical and Process Engineering, The University of Leeds, Leeds, LS2 9JT, UK
† School of Engineering, The University of Edinburgh, Edinburgh EH9 3DW, UK

Keywords: Biomass Combustion, Fuel Flexibility, Power Generation

Abstract

Power generation from the combustion of solid fuels has been a conventional technology for electricity production in the UK and most of the world for many decades. While the phasing out of coal as a fuel is an important aspect of the 'decarbonising' the electricity sector, the respective power plant technology could still play an important role into the future by use of abundant sources of solid biomass fuels. If such resources are to be effectively utilised, it is then necessary to accommodate the wide variation in the characteristics and behaviour of biomass fuels. Some of the key challenges in this context include: control of burn-out efficiency for different fuels; predictability of ash behaviour including operational problems and emissions arising from high ash and high potassium content fuels; the fate of fuel nitrogen content and the consequent effects on NOx emissions. This article presents an overview of these issues, their significance in the context of power plant design and operation and details of some recent research seeking to address them. Results of laboratory scale experiments showing the variation in properties and behaviour of different types of biomass fuel are also presented. These include studies on the relationship between fuel particle size and burn-out duration, gas-phase potassium release from biomass materials during combustion, variability in biomass ash composition and nitrogen release patterns from fuels in high temperature combustion.

1 Introduction

Biomass is classed as a renewable resource and, depending on the means of production, it can be sustainable and provide net benefits in CO_2 emissions by displacing fossil fuels as an energy source. While there are many mature and developing technologies for converting biomass to liquid and gas fuels, one of the more straight-forward means of exploiting biomass energy is the combustion of solid biomass such as in the application of conventional thermal power generation. The term 'conventional power' usually refers to the established large scale thermal power station technology which dominated electricity generation in most countries throughout the 20th century. While these power stations were generally fuelled by the erstwhile 'king coal', the technology is not exclusive to it. In many countries, coal consumption has been displaced in these types of power stations by either co-firing biomass with coal or full conversion to biomass firing. In other cases, power generation using biomass has been deployed in new dedicated plant sometimes as a means of exploiting agricultural by-products, waste wood or municipal solid wastes. While higher proportions of other renewable power sources such as solar and wind are introduced onto the electricity grid (in the UK for example), these are all, to varying degrees, energy sources which are temporally de-coupled from the electrical energy demand. There is therefore a need for demand-side controlled and rapidly despatched power to account for the variations in availability of those sources. Conventional thermal power stations are able to fulfil this role [1, 2]. In pursuing the aim to decarbonise power generation, large-scale coal-fired power or so-called 'conventional power' might be seen by some as being all-but written off [3]. However, full 'de-carbonisation' of the electricity sector may be achievable if this conventional power generation is fuelled by renewable biomass. As the requirement for more renewable power increases globally, it should be expected that new plant for conventional thermal power generation from biomass will be deployed. The large scale feasibility of this has been demonstrated by the success of Drax in North Yorkshire which by 2016 was able to deliver almost 2GW of power from biomass alone.

There are numerous challenges which are faced which will affect the prospects of biomass power generation in the contexts of different countries, not least the need to sustainably source the large quantities of biomass fuel required. Currently, in the UK the vast majority of the biomass fuel consumed for power generation is imported pelletized forestry wood.

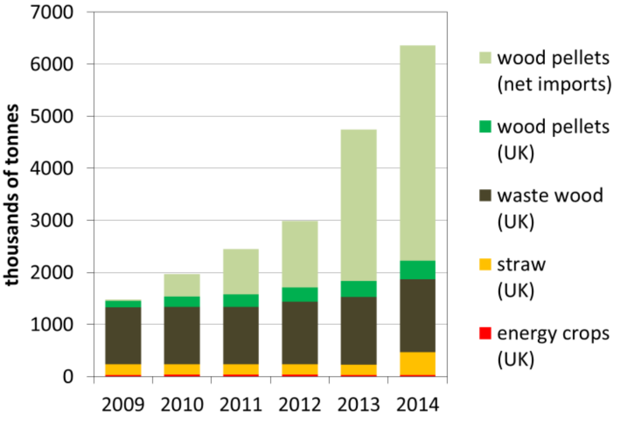


Figure 1 - Biomass fuel supply in UK 2009 to 2014 [4, 5]

However, sustainability and domestic energy security concerns have created interest in using other resources including, in the UK, significant quantities of waste wood, agricultural residues such as straw and dedicated energy crops. As illustrated in

Figure 1 energy crop supply into the biomass fuel market is negligible compared to imported wood pellets although domestic supply of other resources is significant.

Accounting for other wastes and increased land use for biomass energy production, the potential supply is up to 5 times the current level [6]. If all the available biomass resources are to be exploited, the fuels used in power plant should need to include energy crops such as short rotation coppice willow and miscanthus, agricultural by-products such as wheat straw and olive residue as well as managed forestry wood. The variation in the properties of these fuels presents a number of technical challenges which conventional power plant must overcome to achieve "fuel flexibility". Some of the technical challenges associated with the use of conventional power in future scenarios are:

- Variability in fuel combustion behaviour and control of burn-out efficiency for different fuels
- Variability in ash behaviour and the operational problems and emissions arising from high ash and high potassium content fuels
- Fuel Nitrogen content and retention in biomass char during combustion (affecting NOx emissions)

These technical challenges have been targeted by Research Councils UK (EPSRC) in projects such as the Future Conventional Power (FCP) research consortium. The project includes a fuel-flexibility research theme specifically to tackle the technical challenges arising from variations in solid biomass fuels.

2 Fuel variability

There are a number of fundamental differences between the characteristics of coal and biomass. Solid biomass fuels which have typically been used in large scale power plant include coniferous woods such as pine, hardwoods such as eucalyptus, agricultural residues such as straws and olive waste, and energy crops such as miscanthus and short rotation coppiced willow. In composition, the proportions of volatile matter and fixed carbon are a notable difference. Most lignocellulosic biomass (e.g. woody and herbaceous materials) have around 75-85% volatile matter and around 15-17% fixed carbon (dry basis) while bituminous coals have around 30-40% volatile matter and 55-65% fixed carbon [7]. In physical characteristics, the density and thermal properties of coal and biomass particles differ considerably too. Coal particle densities vary from around 1200 to 1400 kg.m^{-3} [8] while solid biomass particle densities range from 200-300 kg.m^{-3} for some herbaceous materials to 500-600 kg.m^{-3} for woody materials. Thermal conductivities of coal particles may range from 0.22 to 0.55 W/m/K [9] while those for biomass particles range from 0.05 W/m/K for some herbaceous materials and between 0.1 and 0.15 for woody materials [10]. The conversion of plant from coal to biomass therefore requires that the differences in combustion behaviour are accounted for in the design of burners and combustion air flow rates to ensure fuel mixing, flame stability and residence times are adjusted for optimum burn-out efficiency.

In addition to the differences in the fundamental combustion characteristics, the difference between the friability of biomass and coal is also of significance. While coal fractures in impact mills, lignocellulosic material, being fibrous, does not fracture well and requires a cutting action for comminution to fine particles. It is consequently more difficult to pulverize solid biomass to obtain particle size distribution in a similar range to that of pulverized coal. The effort used for milling biomass fuel particles to reduce the particle 'top' size needs to be balanced against the effect that the particle size has on the burn-out efficiency. Compared with pulverized coal with particle sizes below 50μm, milled biomass may have particles ranging from 0.1 to 2mm.

There is also variability in combustion behaviour between different types of biomass fuels. Density, thermal conductivity and reaction kinetics can vary significantly and these all have an effect on burn-out. The optimum particle size required for a particular fuel therefore requires characterisation of the material combustion properties. One method for examining this variability is to combust single particles of fuel in a controlled environment and measure the burn-out time. This has been the basis of experimental investigations undertaken by Riaza et al. [11] and Mason et al.[12]. In the latter, an empirical relationship between particle size and the duration of devolatilisation and char-burn out was obtained from single particles burned in a methane flame. The results for a set of 100 observations on particles of eucalyptus in the range 1-20mg are presented in Figure 2.

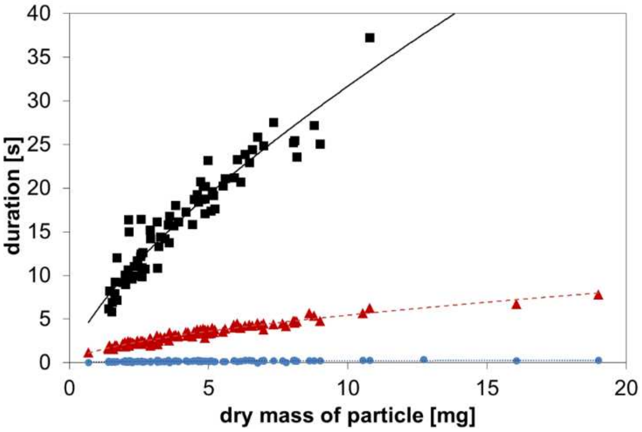


Figure 2 – relationship between particle mass, ignition delay (●), devolatilisation duration (▲) and full burn-out (■) for single particles of eucalyptus wood.

This demonstrates a power function relationship between particle mass and full-burn out such that:

$$t_{burn-out} = a.m_p{}^b \qquad (1)$$

where:

$t_{burn-out}$ is the time for full-burn-out

m_p is the particle dry mass

a and b are empirically derived coefficients

The experimental results from a set of 9 different types of biomass fuels allowed characterisation by evaluation of the coefficients of equation (1). The variability of the fuels evaluated can be seen in Figure 3. For example where a maximum residence time of 2 seconds is necessary to ensure high burn-out efficiency, the optimum particle top-size can vary from around 0.5mm to over 2mm depending on the fuel. This informs the requirements to allow for flexibility in milling system design and burner design.

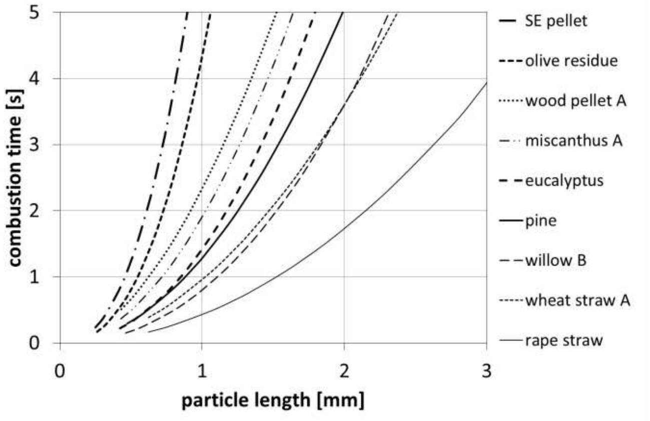
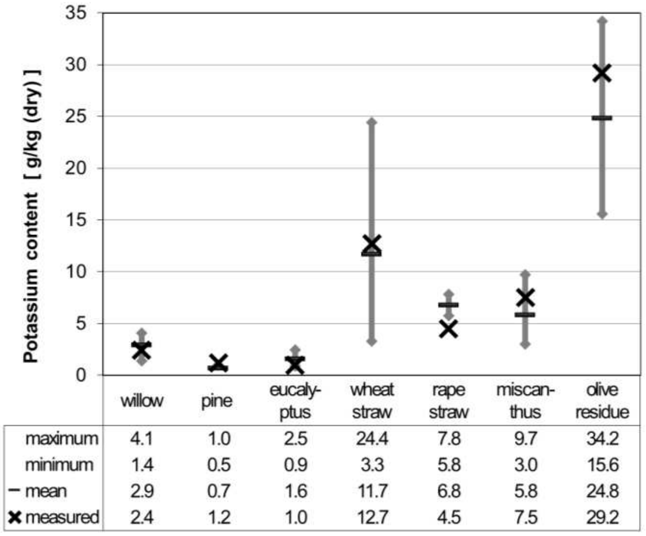


Figure 3 – characteristic burnout times as a function of particle size for various biomass fuel types

3 Potassium content

The inorganic content of biomass fuels varies considerably. The principal components in most woody and herbaceous biomass ash are calcium, silicon, aluminium and potassium as well as smaller quantities of sodium, phosphorous and magnesium. The relative proportions of the ash components determine ash melting behaviour. Other inorganic content includes chlorine and sulphur both of which are likely to be present in the gas phase in the furnace. Potassium is one of the more significant components which both influences ash behaviour and can interact with the gas phase chlorine and sulphur.



	willow	pine	eucaly-ptus	wheat straw	rape straw	miscan-thus	olive residue
maximum	4.1	1.0	2.5	24.4	7.8	9.7	34.2
minimum	1.4	0.5	0.9	3.3	5.8	3.0	15.6
− mean	2.9	0.7	1.6	11.7	6.8	5.8	24.8
✖ measured	2.4	1.2	1.0	12.7	4.5	7.5	29.2

Figure 4 – reported potassium content in various solid biomass fuels (source data: Phyllis2 [7]) compared with measured values for samples analysed in this study.

Potassium is an essential nutrient for plants and trees and is present in significant amounts in most solid biomass fuels. As with the wide ranging variability of many aspects of biomass fuels, potassium content is no exception. An indication of the range of typical potassium content in fuels such as would be typically burned in large-scale power generation plant is illustrated in Figure 4. This includes values measured for some of the fuels noted in Figure 3 along with data extracted from the published online database Phyllis2 [7]. It can be seen from this study that woody biomass has lower potassium present than other biomass although still quantities in the region of 1000 mg/kg or 0.1% weight (dry basis). Herbaceous energy crops and straws tend to have higher quantities and a wider variation. This is especially in the case of straw which is likely affected by different cultivation conditions and treatments. Olive residue is very high in potassium (up to 3% weight) as are other materials derived from seeds and fruits owing to the natural nutrient concentration in these parts of plants.

Combustion temperatures in large scale power plants can range from as low as 1000K (fluidised bed boilers) to over 1600K (pulverised fuel boilers). Such temperatures affect the partitioning of inorganic components through phase transformations. In biomass fuel in particular, potassium, which may be present as various species in solid fuel, is released to the gas phase during combustion at such elevated temperatures. Subsequently, as combustion gases are cooled at furnace surfaces, potassium chloride and hydroxide condense out and lead to increased corrosive deposits and adhesion of ash. Gas-phase potassium can also lead to the formation of sulphate aerosols and re-combine with other solid-phase ash components affecting ash melting behaviour and therefore influencing fouling and slagging in the furnace [13]. In some applications, the level of residual potassium in the char is significant. Since char reactivity is catalysed by potassium content, it is possible that unburned char with high potassium content could continue to burn or re-ignite after leaving the furnace and where ash is accumulated. The ability to determine the degree to which potassium is released from the char during combustion is therefore useful. In order to model this and predict the likely fate of potassium during the combustion process, it is necessary to understand the release mechanisms and patterns of release.

Using a similar experimental method to that used for examining the particle-size/burn-out relationship as described in ref.[12], the gas phase potassium release patterns have been observed using an emission spectroscopy technique. An example of the potassium release patterns obtained from these experiments for various wood pellet fuels is shown in Figure 5. This technique allows estimates of the relative proportions of potassium released to the gas phase in different parts of the furnace and also the amount of potassium which is retained in the solid ash particle [14]. The data has aided the development of models of the combustion of biomass particles which allow investigation of the physical mechanisms by which potassium is released.

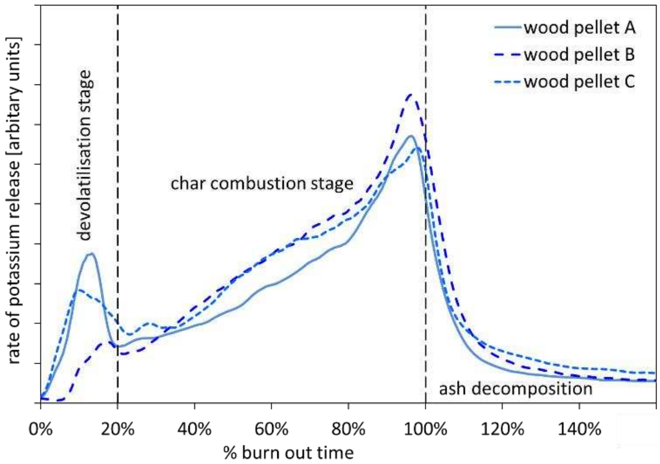


Figure 5 – temporal profiles of gas-phase potassium release for 3 different wood pellets with each stage of the combustion process indicated.

4 NOx emissions

Nitrogen oxide is an atmospheric pollutant specifically targeted by legislation which imposes limits on emissions from large scale plant [15]. There are three different mechanism for NO_x formation during combustion: thermal NO_x, prompt NO_x, and fuel NO_x. Thermal NO_x is formed by the high-temperature reaction of nitrogen with oxygen, it is generally the predominant mechanism in large scale combustion processes. Prompt NO_x is form under fuel rich conditions by reaction between nitrogen, oxygen, and hydrocarbon radicals but is generally much less important compared to thermal NO_x formation at the high temperatures of the combustion processes. Fuel NO_x is formed by the direct oxidation of organo-nitrogen compounds contained in the fuel. Many biomass, especially those from agricultural sources, contain significant amounts of organically bound nitrogen. In high temperature combustion, this nitrogen forms pre-cursor compounds for the formation of nitrogen oxide. During pyrolysis of the fuels part of the Nitrogen will be released as part of the volatile matter compounds, volatile nitrogen and part will remain on the char. Thus, the fate of volatile-N and char-N becomes crucial for the formation of NO, and, hence, for determining the concentrations of NO in solid fuels combustion systems. The volatile-N is transformed into either NO or N_2, while char-N reacts through a set of heterogeneous reactions as the char is oxidized. The overall reaction from fuel Nitrogen to NO or N_2 is influenced by the reaction conditions, specially by the temperature, and the concentration of reducing and oxidizing agents, the turbulence and the residence time in the different combustion zones.

A significant proportion of this fuel-bound nitrogen will be released during devolatilisation as tars and as light gases such as HCN, NH_3 and HNCO [16]. Evolved HCN is considered to be one of the most important volatile N-containing species formed during fuel devolatilisation at high temperatures because it is one of the main precursors of nitrogen oxides. In the presence of oxygen, the oxidation of HCN via NCO produces NO. NH_3 may be formed by direct release from the solid matrix or from the hydrogenation of HCN on the char surface [17].

Under fuel-rich condition, the presence of large amounts of hydrocarbons from pyrolysis, unburnt char and CO favoured the reduction of NO to HCN, NH_3 and molecular nitrogen N_2

Most of the biomass fuels release high amounts of volatiles (about 75% at temperatures above 800 ºC) and the fuel-N is predominantly liberated as NH_3, which may be oxidised to NO but also act as a reducing agent in further reactions with NO to form N_2 [18]. On the other hand, coals released less volatiles and the fuel-N is mainly evolved as HCN, which has a lower potential to reduce NO to N_2 [19].

The control of NO_x produced thermally from air-nitrogen at very high temperatures is achieved by established methods of secondary and tertiary air mixing in pulverized fuel furnaces. This way the flame peak temperature is reduced that leads to less NO_x formation. This effective technique for reducing thermal NO_x, is called air stage combustion.

Munir et al [20] compared the effects of air-staging and biomass addition showing the relationship among the over fire air (OFA) injection location stoichiometric ratio and NO reduction efficiency in a drop tube reactor. It was found that a decrease in primary zone stoichiometry (SR_1) and an increase in residence time, by varying OFA port location in the primary zone, both have a positive effect on NO reduction for coal and coal–biomass blends co-firing.

Man et al. [21] tested series of world-traded coal samples using a high temperature wire mesh apparatus (HTWM) in order to assess the relationship between high temperature (1600°C) char nitrogen content and NO_x formation in Hemweg Power Station using deep furnace air staging. This studies confirmed a linear relationship between high temperature char nitrogen and NO_x formation. These results suggest that high temperature char N content is the main factor limiting NO_x emissions with deep air-staged combustion. Similar experiments on a HTWM are being undertaken at the University of Edinburgh to measure high temperature char Nitrogen content of various biomass in order to estimate the deep air-staged NO_x emissions during the combustion of biomass.

5 Conclusions

Future conventional power plant will likely use some of the wide ranging resources of biomass available. Plant design and operation will need to be able to account for the variability in the fuel combustion characteristics. Milling for specific fuel particle size will need to be managed to ensure optimum burn-out efficiencies. Prediction of the behaviour of inorganic components in the furnace, and in particular the role of potassium, will be needed to enable effective management of ash fouling and deposition. Understanding of NO_x formation mechanisms will also be required to control combustion in a way that minimises emissions. All these issues are being pursued in the research activities described in this article which have been undertaken as part of the UK “Future Conventional Power” research consortium funded by Research Councils UK. The consortium includes projects on various aspects of conventional power plant pertinent to the future use of such plant in the changing context of the electricity generation mix and the target of reducing coal combustion. The consortium partners for the investigation of the issues discussed here regarding fuel flexibility include the Universities of Leeds and Edinburgh and support from industrial partners SSE and GE-Power.

Acknowledgements

The authors are grateful to the Research Councils UK Energy Programme (Grant EP/K02115X/1) for financial support.
P. E. Mason thanks The University of Leeds for the award of a postgraduate scholarship.
Acknowledgements to project partners D. Waldron (GE-Power) and R. Chaggar (SSE Generation) and to the consortium director S. Hogg (Durham University).

References

1. Roth, H., Kuhn, P., and Wagner, U., 'Effects of Wind Energy on Thermal Power Plants', in, Clean Electrical Power, 2007. ICCEP '07. International Conference on, (2007)
2. Ummels, B.C., Gibescu, M., Pelgrum, E., Kling, W.L., and Brand, A.J., 'Impacts of Wind Power on Thermal Generation Unit Commitment and Dispatch', Ieee Transactions on Energy Conversion, 2007, 22, (1), pp. 44-51.
3. DECC, Press Release: New Direction for Uk Energy Policy', (GOV.UK, 2015)
4. Forestry_Commission, Forestry Statistics', (Forestry Commission, 2016)
5. DEFRA, Wood Waste: A Short Review of Recent Research', (Department of Environment, Food and Rural Affairs, 2012)
6. Perry, M. and Rosillo-Calle, F., 'Recent Trends and Future Opportunities in Uk Bioenergy: Maximising Biomass Penetration in a Centralised Energy System', Biomass and Bioenergy, 2008, 32, (8), pp. 688-701.
7. Phyllis2, Phyllis2 - Database for Biomass and Waste', (Energy Research Centre of the Netherlands ECN, 2013)
8. Speight, J.G., Handbook of Coal Analysis, (Wiley, 2005)
9. Herrin, J.M. and Deming, D., 'Thermal Conductivity of U.S. Coals', Journal of Geophysical Research: Solid Earth, 1996, 101, (B11), pp. 25381-25386.
10. Mason, P.E., Darvell, L.I., Jones, J.M., and Williams, A., 'A Comparative Study of the Thermal Conductivity of Solid Biomass Fuels', Energy & Fuels, 2016.
11. Riaza, J., Khatami, R., Levendis, Y.A., Álvarez, L., Gil, M.V., Pevida, C., Rubiera, F., and Pis, J.J., 'Combustion of Single Biomass Particles in Air and in Oxy-Fuel Conditions', Biomass and Bioenergy, 2014, 64, (0), pp. 162-174.
12. Mason, P.E., Darvell, L.I., Jones, J.M., Pourkashanian, M., and Williams, A., 'Single Particle Flame-Combustion Studies on Solid Biomass Fuels', Fuel, 2015, 151, (0), pp. 21-30.
13. Bryers, R.W., 'Fireside Slagging, Fouling, and High-Temperature Corrosion of Heat-Transfer Surface Due to Impurities in Steam-Raising Fuels', Progress in Energy and Combustion Science, 1996, 22, (1), pp. 29-120.
14. Mason, P.E., Darvell, L.I., Jones, J.M., and Williams, A., 'Observations on the Release of Gas-Phase Potassium During the Combustion of Single Particles of Biomass', Fuel, 2016, (in review)
15. DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast) (2010) Official J Eur Union, (L334), pp. 17-119.
16. Wargadalam VJ, Löffler G, Winter F and Hofbauer H, 'Homogeneous formation of NO and N2O from the oxidation of HCN and NH3 at 600-1000 ºC'. Combustion & Flame, 2000, 120, pp 465-478.
17. L Álvarez, J Riaza, MV Gil, C Pevida, JJ Pis, F Rubiera 'NO emissions in oxy-coal combustion with the addition of steam in an entrained flow reactor', Greenhouse Gases: Science and Technology, 2011, 1 (2), 180-190
18. Aihara T, Matsuoka K, Kyotani T and Tomita A, 'Mechanism of N2 formation during coal char oxidation' Proceedings of the Combustion Institute, 2000, 28, pp 2189-2195.
19. J. Riaza, J., Álvarez, Gil, M.V., Pevida, C., Rubiera, F., Pis, J.J, 'Ignition and NO emissions of coal and biomass blends under different oxy-fuel atmospheres.' Energy Procedia, 2013, 37, pp 1405-1412.
20. Munir, S., Nimmo, W., Gibbs B.M. 'The effect of air staged, co-combustion of pulverised coal and biomass blends on NOx emissions and combustion efficiency', Fuel, 2011, 90, 1, pp. 126–135
21. Man, C.K., Gibbins, J.R., Witkamp, J.G. and Zhang, J., 2005, ‘Coal characterisation for NOx prediction in air-staged combustion of pulverised coals’, Fuel 84, pp 2190–2195.