Institution: University of Kent

Unit of Assessment: 15 General Engineering

Title of case study: Combustion instrumentation for power plant optimization

1. Summary of the impact (indicative maximum 100 words)

Instrumentation technologies developed at Kent, in particular pulverised fuel flow metering, on-line particle sizing, on-line fuel tracking and burner flame imaging, have enabled combustion engineers to diagnose large-scale complex combustion processes and optimize the operation of coal, biomass and heavy-oil fired power plants. The technologies operate on novel sensing and advanced measurement principles and have produced real-time measurement and plant condition monitoring data that were previously unavailable. Instrumentation systems operating on the technologies have been applied successfully to a range of pilot plants and on full-scale power plants in countries including the UK, France, China and Saudi Arabia. Work has enabled the power industry to produce electricity safely while minimising environmental impact and employing a diverse range of fuels. The instrumentation technology informed the conversion of Drax power station from 100% coal firing to biomass/coal co-firing during 2011/2012 as it sought to halve its carbon footprint within five years. The technology sourced and informed the alleviation of significant vibration problems within a heavy-oil fired power plant in Saudi Arabia.

2. Underpinning research (indicative maximum 500 words)

New instrumentation technologies have been developed at Kent to tackle the challenges in the 'dynamic' measurement of pneumatically conveyed pulverised fuel (coal and biomass) in fuel injection pipelines. The flow parameters include velocity, mass flow and size distribution of particles [2,6]. Novel electrostatic and imaging sensors in conjunction with digital signal and image processing algorithms have been developed to measure the flow parameters [2,6]. Quantitative data on the dynamics of pulverised coal and biomass-coal blends in fuel injection pipelines allow plant operators to detect variations in fuel supply and oscillations in the flow at an early stage and enables them to balance fuel distribution between fuel injection pipelines, leading to higher thermal efficiency and lower pollutant emissions. Another area of extensive research at Kent is burner flame imaging. Imaging devices, spectroscopic modules and image fibre bundles along with image processing algorithms have been deployed to measure a range of flame characteristics [3,4,5]. These include flame temperature distribution, soot concentration, oscillation frequency, radiative profiles of free radicals and flame stability. Such information is important for plant optimisation and emissions reduction. Global fluctuations in coal price and logistic uncertainties mean that many power plants are burning a diverse range of fuels both indigenous and imported. Without an effective on-line fuel tracking system, pulverising mills and burners may not be optimally configured for the type and quality of the fuel. Unlike conventional techniques that operate on radiometric, microwave or passive tagging principles, the fuel tracking technology developed at Kent is based on flame fingerprinting through novel optical sensing and soft-computing [1].

The team who contributed to this area of impact includes Y. Yan (2004-, Professor), G. Lu (2004-, Senior Lecturer), P. Lee (1991-, Senior Lecturer) and C. Birch (1980-, Research Technician). Key researchers who worked with the team include Dr R. M. Carter (2005-2012), Dr J. Krabicka (2010-2011), Dr T. Qiu (2010-2012), Dr J. Q. Shao (2008-2011), Dr D. Sun (2013-) and Dr L. J. Xu (2002-2005). The team has undertaken research in flow metering of pulverised coal/biomass [3,4,6], on-line particle sizing [3], on-line fuel tracking [1], and burner flame imaging [2,5] since Yan and Lu joined Kent in 2004. The work is funded by the EPSRC, BCURA (British Coal Utilisation Research Association, http://www.bcura.org/), BF2RA (The Biomass and Fossil Fuel Research Alliance, http://www.bf2ra.org/), DTI/TSB and the European Union in collaboration with industrial organisations such as RWE npower, Drax Power, Alstom Power, E.ON, Doosan Babcock Energy, SNET (France) and China Datang Corporation (one of five major Chinese companies in the electricity production sector). Many of the projects were undertaken in collaboration with academic partners in the UK (Cambridge, Cranfield, Edinburgh, Imperial College, Leeds, and Nottingham), France (École des Mines de Douai and Université de Rouen), and China (Tianjin, Tsinghua, Xi'an Jiaotong, Zhejiang and North China Electric Power Universities). More than ten post-doctoral RAs

and eight exchange researchers from France and China have worked with the team since 2004. Extensive demonstration trials of the Kent instrumentation systems have been conducted on pilot plants and power stations in the UK, France, China and Saudi Arabia.

Kent's flame imaging technology was recognised by the global award for innovation at the IET Innovation in Engineering Awards in 2006 "*for developing a new way of measuring the properties of flames in large industrial buildings such as power stations. Combining simple optical components with highly advanced image processing software, they can now establish in real time its stability and pollution performance. This offers enormous benefits enabling the facility to operate more efficiently, as well as reduce the environmental impact*". Further recognition of their contributions to the development of new combustion instrumentation followed. The Kent Team was awarded the Rushlight Commendation Award in 2009, the Best Poster Prize at the International Conference on Sensors & their Applications XV in 2009, the Alec Hough-Grassby Award by the Institute of Measurement and Control in 2011 and an Industrial Award by the IEEE Instrumentation and Measurement Society in 2012. The total value of research awards for underpinning the impact since 2004 was over £2 million and key grants are specified in Section 3.

3. References to the research (indicative maximum of six references)

References to the key outputs (references [4]*, [5]* and [6]* best indicate the quality of the underpinning research):

[1] Xu L., **Yan Y.**, Cornwell S., Riley G., 'Online fuel tracking by combining principal component analysis and neural network techniques', IEEE Transactions on Instrumentation and Measurement, vol.54, no.4, pp.1640-1645, 2005. DOI: 10.1109/TIM.2005.851203. *This output underpins Kent's pioneering work in online fuel tracking through advanced flame monitoring.*

[2] Carter R.M., **Yan Y.,** Cameron S.D., 'On-line measurement of particle size distribution and mass flow rate of particles in a pneumatic suspension using combined imaging and electrostatic sensors', Flow Measurement and Instrumentation, vol.16, no.5, pp.309-314, 2005. DOI: 10.1016/j.flowmeasinst.2005.03.005. *This output underpins Kent's contributions to on-line particle sizing and mass flow metering.*

[3] **Lu G.**, **Yan Y.**, Colechin M., Hill R., 'Monitoring of oscillatory characteristics of pulverized coal flames through image processing and spectral analysis', IEEE Transactions on Instrumentation and Measurement, vol.55, no.1, pp.226-231, 2006. DOI: 10.1109/TIM.2005.861254. *This output was returned by **Lu** in RAE 2008. It is widely referenced and illustrative of the power of Kent's digital imaging approach to burner flame monitoring.*

[4]* **Lu G., Yan Y.**, 'Temperature profiling of pulverized coal flames using multicolor pyrometric and digital imaging techniques', IEEE Transactions on Instrumentation and Measurement, vol.55, no.4, pp.1303-1308, 2006. DOI: 10.1109/TIM.2006.876393. *This paper underpins Kent's work on digital imaging based flame temperature distribution measurement.*

[5]* **Lu G.**, **Yan Y.**, Cornwell S., Whitehouse M., Riley G., 'Impact of co-firing coal and biomass on flame characteristics and stability', 2008, Fuel, vol.87, no.7, pp.1133-1140. DOI: 10.1016/j.fuel.2007.07.005. *This output, submitted by **Yan** to REF 2014, demonstrates how Kent's digital imaging approach is applied to characterise biomass-coal co-firing flames.*

[6]* Qian X.C., **Yan Y.**, Shao J.Q., Wang L., Zhou H., Wang C., 'Quantitative characterization of pulverized coal and biomass-coal blends in pneumatic conveying pipelines using electrostatic sensor arrays and data fusion techniques', Measurement Science and Technology, vol.23, no.8, 2012. DOI: 10.1088/0957-0233/23/8/085307. *This output, submitted by **Yan** to REF 2014, illustrates Kent's electrostatic sensing technology for the flow monitoring of pulverised coal and biomass-coal blends.*

Key research grants

Yan, Technology Strategy Board (Technology Programme, Ref: TP/2/SC/6/I/10064) "An integrated sensor system for combustion plant optimisation", £512k, 2005-2008.

Yan, EU & Government Office for the South East (Interreg III, Ref: 309), "Optimization of combustion plant through advanced measurement & computer modelling", €501k, 2006-2008.

Yan, BCURA(B90) "Dynamic and movement behaviours of biomass/coal flow", £70k, 2007-2010.

Yan, Lu and Lee, EPSRC (EP/F061307) "Optimization of biomass/coal co-firing processes through integrated measurement and computational modelling", £411k, 2008-2011.

G Lu, EPSRC (EP/G002398) “Quantitative characterisation of flame radical emissions for combustion optimisation through spectroscopic imaging”, £256k, 2009-2011.
Yan and Lu, EPSRC (EP/G063214) “In-depth studies of oxycoal combustion processes through numerical modelling and 3D flame imaging”, £319k, 2009-2012.
Yan and Lu, EPSRC/E.ON (EP/G062153) “EPSRC-E.ON Strategic Partnership, Carbon Capture and Storage: OxyCAP UK”, £169k, 2009-2013.
Yan and Lu, BF2RA (Biomass Fossil Fuel Research Alliance, Ref: Project #2) “Intelligent flame detection”, £50k, 2010-2013.

4. Details of the impact (indicative maximum 750 words)

The Kent team has been working closely with industrial organisations such as Alstom Power, E.ON, Doosan Babcock Energy, EDF Energy and RWE npower through previous and existing research projects since 2004. Since 2008 the team has undertaken consultancy work for RWE npower, Drax Power, E.ON, International Innovative Technologies and Land Instruments International. The power industry as a whole and, in particular, power generation organisations in the UK, China, France and Saudi Arabia have gained direct and indirect benefit from these research and consultancy activities. Fuel handling, fuel tracking and flame monitoring practice has been influenced in the power industry as have the design and implementation of new and existing instruments.

The Kent team has supported power plant engineers in diagnosing and optimising the operation of full-scale coal, biomass and oil fired power plants in the UK [S1, S2], China [S3, S4] and Saudi Arabia [S5] through the application of their instrumentation systems. As one example, the availability of the Kent flame imaging technology has made direct impact on the diagnosis and optimised operation of biomass/coal and oil fired power stations. Drax is the largest power plant in the UK with its output capacity of 4,000 megawatts, making it nearly twice the size of the next largest coal-fired power station in the UK. It provides enough power to meet 7% of the UK’s electricity needs and, to reduce carbon dioxide emissions, converted three of its six generating units to burn sustainable biomass in place of coal during 2011/12 in order to halve its carbon footprint within five years. The Kent team operated their state-of-the-art flame imaging system on Drax to acquire fundamental flame data [S2]. The technology allowed quantitative comparisons between different burners some of which were coal fired, some biomass fired and some biomass/coal co-fired. The combustion engineers at Drax were able to consider all relevant quantitative flame characteristics and their correlations with plant configurations and pollutant emissions. Such information has direct implications on the safe and efficient operation of biomass and biomass/coal fired power plants.

Electricity generation is a key issue in Saudi Arabia given the high and increasing demand for power – some 27 million people face sporadic power cuts due to power surges from the operation of air conditioning systems. To help address this problem a 660 megawatts, heavy-oil-fired power station was built in 2012. This encountered significant furnace vibration problems. The Kent team was invited to join an investigative team to identify the cause of the boiler vibration [S5]. It was concluded that unstable flames are a significant contributory factor, leading to serious thermo-acoustic vibration of the furnace. The flame imaging data from the Kent instrumentation system provided significant diagnostic information for the investigators and plant operators, which has enabled them to successfully resolve the vibration problem.

Yan has been invited to give keynote lectures at seven international conferences (IEEE EUROCON, INFUB, IFRF, IEEE ICSIMA, IEEE IST, IEEE ISICT and ISMTMF) since 2008, many of which were attended by power plant operators and combustion engineers [S6, S7], in addition to technical presentations at industrial organisations (e.g. Alstom Boilers, Beijing Huaneng Thermal Power Station (China), Cottam Power Station, Drax Power, Greenbank Group, Hamworthy Combustion, Laborelec (Belgium) and Tilbury Power Station). The research outputs from the Kent team have been widely referenced by industrial practitioners [S4-S7]. The Kent team successfully ran two UK-China Summer Schools both funded by RCUK China (SS08-025 and SS10-017), in 2008 and 2010, respectively, which were attended by engineers from the power generation industry. Yan and Lu are contributing actively to a wide range of activities of learned societies and

professional organisations including the IEEE Instrumentation and Measurement Society, the Coal Research Forum, the Institute of Measurement and Control, the Energy Institute and British Flame Research Committee. The flame imaging work was reported in television programmes and on-line media following the Rushlight Commendation Award in 2009 (http://www.rushlightevents.com/rushlight-awards/background/roll-of-honour/).

These measurement and monitoring technologies have enhanced the capability of the power industry to burn low quality coals and renewable fuels such as biomass and to reduce pollutant emissions. Meanwhile, the resulting safe, efficient use of low quality coal, biomass and heavy oil for power generation means that electricity is now produced from cheaper fuels leading to lower electricity costs for consumers. The availability of new technologies has also enabled conventional power plants to fire a wider range of biomass fuels and thus reduce their dependence on fossil fuels with a significant implication for energy security and a considerable reduction in pollutant emissions. Lowering carbon emissions in power generation not only benefits the UK and the international economy but also has a positive impact on the global environment. The combustion instrumentation research at Kent has made a great impact on efficient operation of coal and biomass fired power plants in Far Eastern countries such as China where 70% of energy is generated from coal fired power plants. The increasing use of biomass for power generation in these countries is playing a major role in reducing greenhouse gas emissions on a much greater scale. Due to the 'enabling' nature of the research, it is difficult to quantify directly the economic and environmental benefits to power generation and related industries such as steel and cement production. Such plants are complex systems with thousands of variables. However, the benefits cannot be underestimated in view of the scale of the industries across the globe. For example, within a typical coal fired power plant, unoptimised units readily produce CO at full load. Optimising the pulverising mill settings with the use of the Kent fuel tracking system has been shown to "free up" typically 19kg/s air and thus prevent CO breakaway on the unit. On the basis of 1000ppm CO production equating to 3.77MJ/s loss, this gives an annual benefit of £91.5k per unit if the pulverising mill settings are optimised using the fuel tracking systems alone [S8].

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1: Corporate Engineer from RWE npower will confirm the application of Kent's pulverised fuel metering, on-line particle sizing and fuel tracking technologies to their biomass fired power stations

S2: Principal Scientist from Drax Power will confirm the application of Kent's flame imaging technology on Drax Power Station during conversion from coal firing to biomass/coal co-firing.

S3: Chief Engineer from China Datang Corporation will confirm the impact of Kent's pulverised fuel flow metering technology on the operation of their Weihe Power Station operated by China Datang Corporation.

S4: Technical Manager from Huadian Tianren Electric Power Control Technology Co., P. R. China will confirm Kent's pulverised fuel flow metering and on-line particle sizing technologies on the operation of coal fired power stations in China.

S5: Vice Director of the Institute of Thermal Power Engineering at Zhejiang University, P.R. China will confirm how Kent's flame imaging technology contributed to resolving the boiler vibration problem at a power station in Saudi Arabia (this contact led the international team investigating the vibration problem).

S6: Chairman of the 9th European Conference on Industrial Furnaces and Boilers (INFUB 2011) will confirm Yan invited to give a keynote lecture at INFUB 2011, which was attended mostly by industrialists in the power industry.

S7: Associate Professor from École des Mines de Douai, France and Chairman of the French National Committee of the IFRF (International Flame Research Foundation) will confirm Kent's collaboration with French partners including work with SNET and Yan being invited to give a keynote lecture at the 17th IFRF Members Conference 2012, which was attended mostly by industrialists in the power industry.

S8: Senior Project Manager from RJM International will confirm the economic impact of the on-line tracking technology on the operation of coal fired power stations.