Advanced sensors and smart controls for coal-fired power plant

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Preface

This draft report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

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Abstract

Coal power plant control systems have progressively evolved to meet the growing demand for efficient and flexible power generation whilst maintaining low emissions. In particular, optimisation of the combustion process has required increased use of online monitoring technologies and the replacement of standard control loops with more advanced algorithms capable of handling multivariable systems. Improved stoichiometric control can be achieved with coal and air flow sensors or imaging and spectral analysis of the flame itself, whilst in situ laser absorption spectroscopy provides a means of mapping CO and O_2 distribution in hot regions of the furnace. Modern plant control systems are able to draw on a range of computational techniques to determine the appropriate control response, including artificial intelligence which mimics the actions of expert operators and uses complex empirical models built from operational data. New sensor technologies are also being researched to further improve control and to withstand the high temperature and corrosive environments of advanced coal plant and gasifiers. Increased use of optical technologies is of particular interest, with sensors based on optical fibres able to perform low noise, highly sensitive, and distributed measurements at high temperatures. Microelectronic fabrication techniques and newly developed high temperature materials are also being combined to develop miniaturised devices which provide a robust and low cost solution for in situ monitoring of gases and other parameters. These new sensors can be integrated with wireless communication technology and self-powering systems to facilitate the deployment of distributed sensor networks and monitoring of inaccessible locations. Using principles of self-organisation to optimise their output, such networks may play a growing role in future control systems.

Acronyms and abbreviations

APC	advanced process control
CCTV	closed-circuit television
CCD	charge coupled device
CLD	chemiluminescence detector
CMOS	complementary metal-oxide semiconductor
CV	controlled variable
DCS	distributed control system
EPRI	Electric Power Research Institute
EEGT	economiser exit gas temperature
FEGT	furnace exit gas temperature
FD	forced draught (fan)
FPI	Fabry-Pérot Interferometer
FTIR	Fourier transform infrared
GC	gas chromatography
GIF	graded index fibre
HCF	hollow core fibre
HMI	human machine interface
ID	induced draught (fan)
IGCC	integrated gasification combined cycle
LIBS	laser induced breakdown spectroscopy
LVDT	linear variable differential transformer
MEMS	microelectromechanical systems
MIMO	multi input-multi output
MPC	model predictive control
MV	manipulated variable
NETL	US National Energy Technology Laboratory
NDIR	non-dispersive infrared
OFA	overfire air
PCF	photonic crystal fibre
PDC	polymer-derived ceramic
PLC	programmable logic controller
PGNAA	prompt gamma neutron activation analysis
RTD	resistance temperature detector
UV	ultraviolet
vis	visible light
SCR	selective catalytic reduction
SISO	single input-single output
SMF	single mode fibre
SNCR	selective non-catalytic reduction
TDLAS	tunable diode laser absorption spectroscopy

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1 Introduction

There is growing environmental and economic pressure on coal-fired power plants to operate with high efficiency, reduced emissions, and with high flexibility to accommodate power grids with growing proportions of intermittent renewable sources. With rapid advances in computing power, process control algorithms, and sensor technologies, optimisation of the plant control system is an increasingly powerful means of meeting each of these challenges. Such is the current dominance of fossil fuel power in the global energy mix, even incremental efficiency improvements derived from plant optimisation can lead to significant environmental gains. Furthermore, emerging high efficiency coal power technologies such as advanced ultra-supercritical plant (A-USC) and integrated gasification combined cycle plants (IGCC) are imposing more demanding criteria for sensors which are able to operate in harsh environments (NETL, 2013).

Modern coal power plants rely on a complex network of sensors, actuators, digital controllers, and supervisory computers to operate and coordinate each of the plant subsystems. Hundreds of feedback control loops serve to monitor plant processes and perform appropriate control actions, aiming to maintain optimum operating conditions regardless of system disturbances such as changes in coal quality or load demand. However, the highly interrelated nature of power plant parameters means that close control is highly challenging, and the plant is often not operated to the limit of its potential capabilities. Since the late 1990s, the power sector has increasingly adopted more advanced control techniques, often originally developed for the process industries, which perform computational optimisation of complex systems using advanced algorithms and empirical models. Such techniques are particularly effective for balancing high efficiency and low emissions in the combustion process, where often significant economic returns have been made. Optimised coordination of the boiler and turbine has also enabled more flexible plant with faster start-up and load-following response.

To fully exploit the benefits of enhanced control systems, accurate and continuously updated data are needed to form a more complete picture of the current plant state. This is particularly the case in combustion systems where, in contrast to the steam cycle and turbine, there is a relative paucity of in situ, online sensors, whether for pulverised coal furnaces, gasifiers, or gas turbines. This is largely due to the demanding environments in these systems, including high temperatures and corrosive conditions which severely limit the lifetime of electronic devices and prevent many sensor mechanisms from functioning properly. Instead, extractive techniques which sample the furnace environment are often employed which introduce delay and are not continuous. Besides control applications, the need for sensors in such areas of the power plant is furthered by the potential benefits of accurate condition monitoring, allowing equipment faults to be predicted in advance and dealt with in the most economically optimal way.

Advances in materials research and microfabrication techniques are presenting new solutions for high-performance, robust sensors, of which optical sensors and advanced microelectronic sensors have been identified by the US NETL as amongst the most promising. Optical fibres can be used both for signal transmission and, if appropriately modified, as transducers which encode physical parameters as some property of light. Handling sensory information in the form of light has the benefit of immunity to electromagnetic noise, and optical fibre materials have potentially high resistance to very high temperatures. A wide range of optical fibre devices for sensing applications has been developed since the 1980s, and current research is exploring their use in power systems through incorporation with gas-sensitive materials and new fabrication methods. Other advanced optical techniques already providing benefits in coal plant include the use of tunable lasers for highly accurate in-furnace spectroscopy and flame imaging with fibre optic bundles

Microelectronic sensors derived from thin film fabrication techniques and new temperature-resistant ceramic semiconductors can provide low cost, robust, and miniaturised sensor packages. Such microsensors offer the advantage of in situ monitoring in previously inaccessible locations and harsh environments, and deployment in larger numbers. In particular, the development of new mechanisms for gas detection at high temperatures could allow microsensors replace extractive spectroscopic techniques for control applications. To fully benefit from dense networks of miniaturised sensors, they must be integrated with the wireless sensor technologies which have seen increasing use in power plants over the last decade. Aside from enabling more economic and flexible networks, wireless networks of smarter sensors could represent the next step in truly distributed power plant control.

This report will briefly summarise the architecture of a power plant control system, for which a more detailed description may be found in Nalbandian, 2001. Some of the advanced techniques currently available for process control will then be considered, followed by a review of how these methods can be combined with current sensor technologies for combustion optimisation in pulverised coal units. The final three chapters address recent research activity on the next generation of sensors for combustion and power systems, covering the fields of optical sensing, high-temperature microsensors, and developments in the use of wireless sensor networks.

2 Overview of coal plant control

2.1 Sensors and actuators

An array of sensors and actuators associated with each plant process forms the frontline of a power plant control system. Sensors transduce physical parameters within the process such as temperature, pressure, or chemical concentration, into an electrical or optical signal which can be used to determine an appropriate control action or simply monitored. The necessary process changes are then effected by actuators such as the motors and drives which control valves, dampers, burner position, and coal feeders. Some actuators of particular importance, such as the main steam valve to the steam turbine, are equipped with dedicated sensors to feedback their position and ensure an accurate control response.

Table 1 Some of the key parameters measured in coal plant processes and associated online sensor technologies

Plant process	Parameter	Common sensor technologies
Furnace	Coal flow Combustion air flow Temperature Oxygen CO Presence/quality of flame Heat flux	Electrostatic or microwave-based Pitot tubes, Venturis, thermal mass flow meters Thermocouple, IR or acoustic pyrometry, TDLAS Electrochemical cell, paramagnetic NDIR, catalytic bead, TDLAS UV/vis/IR detector, optical imaging Heat flux sensors (thermocouple or RTD-based)
Steam cycle	Feedwater pH Feedwater O_2 Feedwater solids Drum level Steam temperature Steam pressure Steam flow	Electrochemical Electrochemical, polarographic cell Specific conductance Radar sensors, optical Thermocouple and RTD Bourdon tube, piezoelectrics, diaphragm gauge Coriolis meter, vortex meter, Venturi
Emissions monitoring and pollutant control	NO and NO_2 SO_2 Hydrocarbons CO Particulates NH_3 slip $H_2/CO_2/CH_4$ Limestone slurry pH Mercury Carbon-in-ash	CLD, UV photometry, electrochemical cell NDIR, UV photometer, FTIR Flame ionisation detector NDIR, catalytic bead Optical opacity UV photometry, diode laser/mid-IR absorption Thermal conductivity detector Electrochemical UV absorption Microwave-based
Coal mills	Coal moisture Coal elemental composition Particle size Coal flow	Microwave-based LIBS, PGNAA Optical Electrostatic or microwave-based
Steam turbine	Main valve position Blade tip timing and clearance	LVDT Optical, eddy current, capacitive
Auxiliary machinery	Temperature Vibration	RTD, thermocouple Accelerometer

Table 1 provides a non-exhaustive summary of the range of parameters and associated sensing technologies which can be employed in the various subsystems of a pulverised coal plant. Many of these sensors are by no means essential for basic plant control, but optional additions which can allow for more accurate control or process monitoring, potentially leading to economic, efficiency, or environmental gains. Several sensing applications have competing technological solutions available, with the most suitable depending on plant specifics and the balance between increased cost and potentially greater accuracy of measurement.

Regardless of the parameter measured, generally desirable properties in sensors include (Webster and Eren, 2014):

- high sensitivity;
- high selectivity;
- good resistance to environmental factors (temperature, pressure, corrosion, electromagnetic interference);
- broad sensing range;
- low drift (slow change in the signal over time);
- high signal-to-noise ratio;
- low power requirement;
- longevity;
- low cost.

With respect to power consumption, many commonly used sensors, such as thermocouples and photodiodes, are 'passive' and generate their own electric signal. In contrast, active sensors such as pyrometers and spectrometers require an external power source to function. Low power sensors are particularly desirable for their potential in wireless, battery-powered applications.

2.1.1 Smart sensors

In addition to the transduction mechanism or 'sensing element', sensors usually incorporate embedded electronic devices for signal processing and interfacing with the main power plant communication network. This can include signal conditioning such as noise filtering and amplification, and signal processing such as analogue-to-digital conversion (Figure 1). Increasingly, sensors are also integrated with a microcontroller chip which allows them to carry out basic control functions, giving rise to the term 'smart sensor'. As the processing power of microelectronics grows rapidly, sensors have become increasingly 'smarter', representing a trend towards shifting as much control duty as possible to the sensor level rather than being centrally managed (Weber, 2009; Reverter, 2012; Breeze, 2013a).

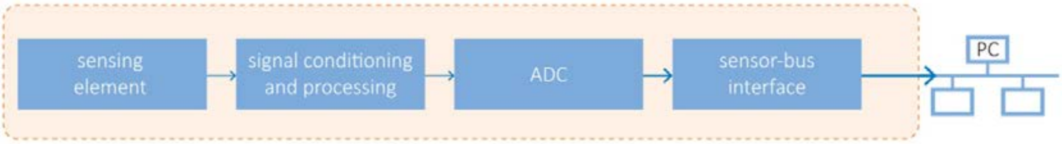

Figure 1 **A smart sensor integrated with signal processing and digital networking capability (ADC, analogue to digital converter)**

Smart sensors can exploit their additional processing capability to generate more useful and accurate data, whilst minimising their power consumption. On a basic level, the device may be able to self-calibrate, store memory, or identify when thresholds are exceeded and activate alarms. Additional functionality may include decision-making such as identifying when to change measurement range, recalibrate or adjust their offset. A smart sensor can also carry out basic computation such as finding data averages and variance.

Improving sensor intelligence can also be a means of circumventing practical limitations on sensor accuracy. For example, the microcontroller can learn about inaccuracies in an individual sensor and compensate for them accordingly. As sensor error is usually non-linear, this correction can also be adjusted appropriately over the sensor range (Blankinship, 2003). Gains in sensor response speed and management of power consumption by minimising unnecessary measurements are other key benefits of smarter sensors.

As the power of miniaturised microcontroller devices grows, sensors are likely to be conferred with increasing processing power and the ability to perform more advanced control functions. The sensor package may also incorporate a transceiver chip for wireless communication and networking with other sensors.

2.2 Control loops

The most basic element of a plant control system, control loops determine the nature and extent of input actions to the plant, whether in the form of the value of a continuous parameter such as valve position, or discrete actions such as turning a process on and off. Control loops which simply relay operator input or a predetermined value, regardless of the process response or current conditions, are known as open loops and are only suitable for the most basic processes. Most process control is instead governed by closed control loops which automatically adjust the control action according to the change effected in some output variable. More generally known as feedback loops, this type of control therefore relies on the data generated by sensors monitoring the process output (Figure 2). The controller typically aims to maintain the output variable at a set point, calculating the extent of the input action using the error between the set point and the measured value fedback by the sensor.

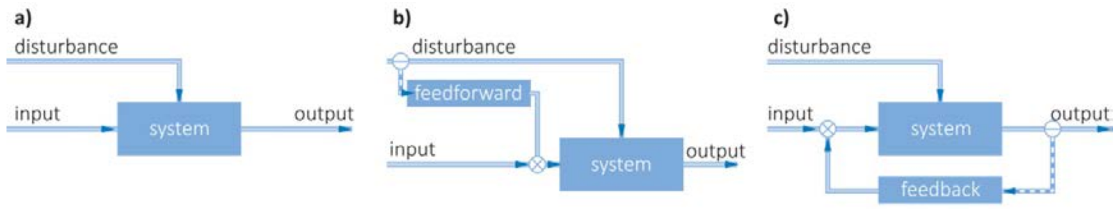

Figure 2 a) Open loop, b) feedforward and c) closed loop (feedback) control

As a control response which is simply proportional to the error can cause the output variable to overshoot or oscillate around the set point, feedback control loops normally also take into account the rate of change and recent history of the output by incorporating derivative and integral functions respectively. Known as proportional-integral-derivative (PID) control, these control loops are ubiquitous in all forms of process control, including power plants. An element of operator input is usually required in such systems, as the optimal weighting (or gain) of each of the three functions must be set in a process known as control loop tuning. Once a control loop has been tuned for a given process, it should be able to operate independently under steady state conditions and for a given operational phase of the plant (start-up, shut-down, constant load) (Leopold, 2009). Supervisory intervention can also be required to set the desired set point and the controller bias, which adjusts the level of the control action according to prevailing operating conditions.

In addition to the controller inputs and outputs, also respectively known as manipulated and controlled variables, are the disturbance variables, which affect the output but are subject to control. For example, for a coal burner controller, disturbance variables include the power plant load demand and the current coal quality. Power plant feedback loops also often incorporate a 'feedforward' element, which adjusts the control output according to changes in disturbance variables, using some knowledge or model of the process response. In this arrangement, the feedforward is used to set the correct action for a given plant load, whilst the feedback control acts to reject other, unmeasured disturbance to the output.

Another layer of complexity which can be added to the feedback loop is adaptive control, where the gain in the feedback response is automatically adjusted (or tuned) over time to account for changes in the system. Although the terminology is not strictly defined, feedforward and adaptive control strategies are sometimes known as advanced regulatory control (ARC), in contrast to the advanced process control techniques discussed in Chapter 3. Despite their incorporation of system models, these ARC measures are single-input single-output (SISO) controllers, which fail to take into account the interrelated nature of all the manipulated variables in the overall power plant system. However, they have many advantages, including the transparency of the process and ease of adjustment for operators, and good performance with controlling non-linear processes (EPRI, 1998).

Whilst PID controllers are a form of analogue control, some plant processes are operated using logic control, which is required for discrete actions such as turning a process on when a given condition is met. Logic control can include combinatorial logic, which takes an action based on analysis of several input conditions, and sequential logic, where the output action depends on the past history of inputs and timing. Examples of this in a power plant include sootblower operation and the activation of gypsum removal from a wet flue gas desulphurisation vessel tank once a certain density is reached (Babcock and Wilcox, 2005).

2.3 Condition monitoring

Power plant sensors also play an essential role in monitoring the physical condition of the plant, particularly for equipment subject to high stresses, vibration, or temperature (Almasi, 2011). Rotating machinery such as pumps, steam turbines, and the generator are particularly in need of condition monitoring to ensure potential faults are detected before equipment failure occurs. This kind of condition-based maintenance (CBM) is an alternative to scheduled inspection or replacement upon failure, and can minimise maintenance costs and downtime. Analysis of strain, temperature, or vibration data from the equipment is compared to baseline levels from normal operation, to detect abnormal readings and deteriorating trends. Where large networks of monitoring sensors are deployed, this analysis can benefit from advanced optimisation software such as ProcessOpt from NeuCo (Johnson, 2010a).

2.4 Distributed control systems

The physical means of implementing and coordinating all the control loops required in industrial processes has evolved in parallel with advances in computation and communication technologies. Early use of computers in a supervisory rule, such as for deciding set points, was superceded by direct digital control (DDC) in the 1960s and 1970s, in which the plant was centrally controlled by a computer. In the 1980s, the availability of microprocessors allowed the development of distributed control systems (DCS) in which many separate controllers are distributed throughout the plant and connected by a communications network for monitoring in a central control room. A DCS can be viewed as a control hierarchy, with a layer of sensors and actuators interacting with the plant processes, a second layer of individual automatic controllers, followed by a supervisory layer in a central control room (Figure 3). The supervisory layer includes a 'human machine interface' (HMI) including graphical displays which allow monitoring, trend charting, and operation of the system by power plant operators (Segovia and Theorin, 2013; Nalbandian, 2001). A list of major DCS suppliers and their products is provided in Table 2.

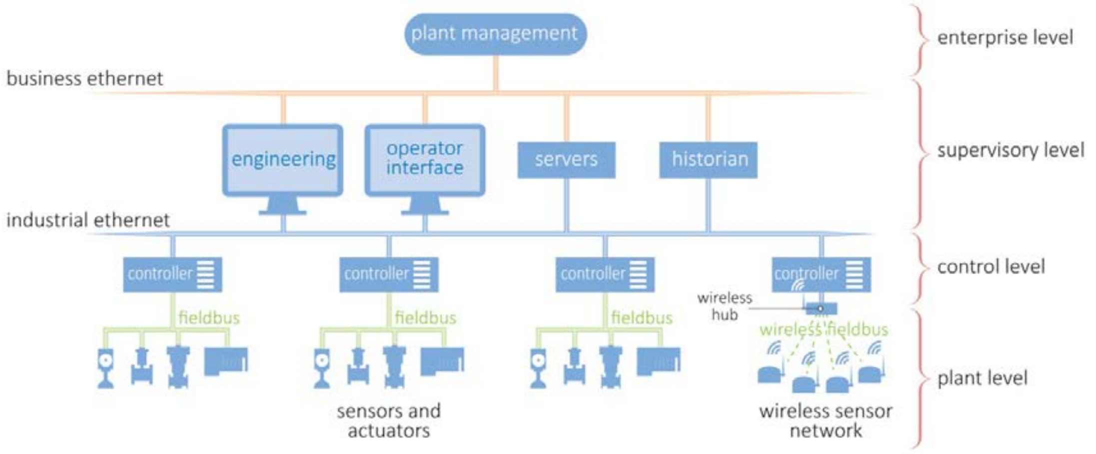

Figure 3 A typical DCS architecture

Table 2 A list of major commercial DCS systems	
Company	DCS
ABB	Symphony
Alstom	Alspa
Siemens	SPPA-P3000
GE	Mark VI
Metso	DNA
Emerson	Ovation
Hitachi	HIACS
Honeywell	Experion
Yokogawa	Centum
Invensys	Foxboro
Rockwell	PlantPAX

DCS continue to evolve as processing power is shifted further towards the plant processes in the form of smart sensors, resulting in even more distributed control. Wireless networking is also changing the physical architecture of the system, potentially even allowing mobile control interfaces. Increased device interaction with the internet, allowing the plant to coordinate with external data such as weather forecasts is also a future possibility (Leimbach, 2009).

An alternative, but compatible, plant control approach to the DCS is the use of programmable logic controllers (PLC), which are special purpose computers originally designed to perform logic and sequential control. Whilst the DCS can be seen as decedent of the panel board controllers used for analogue control, PLC have evolved from the relay switches and mechanical timers once used for discrete control. However, as DCS have always also been capable of performing logic control, and PLC have developed to handle analogue controls, the two systems have become increasingly indistinguishable (Siemens, 2007; Lydon, 2011). DCS are generally able to handle a greater number of input-output combinations and are integrated with human machine interfaces (HMI), so are better-suited for controlling large plant. Hybrid systems are also possible, where individual PLC are connected within a plant-wide DCS network. PLC are still well-suited to performing fast, discrete control for relatively independent auxiliary processes such as water treatment, sootblowing, ash management, particulate control, and condensate polishing.

Above the technical supervisory layer or control room of the DCS is a further layer which deals with the business element of the plant, charged with maximising plant profitability and potentially coordinating output with other plants belonging to the utility.

2.5 Process networking

A key element of the DCS is the ability for the system's component controllers, computers, and workstations to digitally communicate as a coordinated network, in contrast to the serial two-way communication to which early analogue control systems were limited. Digital networks allow data to be quickly shared between devices, and with less noise and more reliable transmission than analogue connections. However, even after the widespread installation of digital controllers in the 1980s, the final layer of communication between the controllers and their devices was still performed over the established analogue current loop, known as 4–20 mA after the limits of its range. In order to harness the benefits of smarter sensors, it was necessary to extend digital communication to the device level and allow for transmission of data beyond the simple process variables supported by the analogue current loop. To this end, manufacturers developed 'fieldbus' communication protocols tailored to real-time distributed control applications, which define the rules by which data are exchanged over the network (Segovia and Theorin, 2013; Murugesan, 2008; Emerson, 2007).

The period of intense competition between these largely incompatible systems is now referred to as the fieldbus wars, with leading systems including Foundation Fieldbus, Hart, Profibus, and Modbus. Rosemount's Hart (highway addressable remote transducer) protocol is unique in that it supports both digital and analogue signals, and is therefore compatible with the existing analogue control loops in legacy power plant (Merritt, 2006). This has led to its widespread adoption in the power industry, although fully digitalised systems such as Foundation Fieldbus are making increasing inroads due to various benefits such as increased speed, reduced noise, and greater flexibility, and despite the need for entirely new communications infrastructure. The more recent spread of the Ethernet communication platform has also extended to most levels of the control network, save for the final link to plant devices, where Ethernet connections are not sufficiently robust for the environment of the plant floor. A new generation of Ethernet compatible fieldbus protocols has been developed from existing products, including Profinet, Foundation HSE, and Ethernet/IP. The current trend towards wireless sensor networks has necessitated the introduction of yet more fieldbus protocols in the form of WirelessHART and ISA 100.11a, amongst others.

2.6 Data historians

In addition to its use in control loops, the large amounts of data generated by the plant sensor network may be archived by proprietary software known as data historians. These programs are able to deal with high flow data streams, compressing and processing them into data sets which can be easily accessed and manipulated by plant operators (Chardin and others, 2013). Besides data archiving usually being a legal requirement for the plant, the ability to study historical plant data is invaluable for monitoring devices, maintenance, informing business and technical decisions, and compiling reports. Historians are required to communicate with the fieldbus and other industrial protocols, group and display data so as to reflect power plant subsystems, and calculate parameters which are not directly measured, such as auxiliary power consumption and efficiency. With rapid increases in computing power available to power plants, the analysis and display of large data sets has become more convenient, and data compression less important.

Historical data can be used in the training of empirical models for process control (Chapter 3) but first requires processing to remove the averaging and smoothing effects of compression routines (Hines and Davis, 2005).

3 Advanced process control

In contrast to the basic single input-single output control provided by PID control loops, advanced process control (APC) generally refers to systems capable of multivariable control, or the simultaneous manipulation of several output variables based on multiple inputs. This kind of control can become necessary when there is significant interaction between two or more control loops in the process, such as the basic interaction between firing rate and MW output control shown in Figure 4. Although such multivariable interactions abound in power plants, APC first emerged in the petrochemical and chemical industries, where single loop controls are wholly inadequate for operating processes such as distillation columns. In the late 1990s, however, APC began to see increasing adoption by the power industry due to the introduction of NOx limits which required much closer control of the combustion process (*see* Chapter 4). This trend was continued as plants in deregulated power markets became obliged to operate with increasing flexibility and load following, in addition to the growing economic and environmental incentives to maintain consistently high efficiencies. APC is now widely used for control tasks such as combustion optimisation, steam temperature control, and boiler-turbine coordination for load control (Vesel, 2009; Spring, 2009; James and Spinney, 2011; EPRI, 1998).

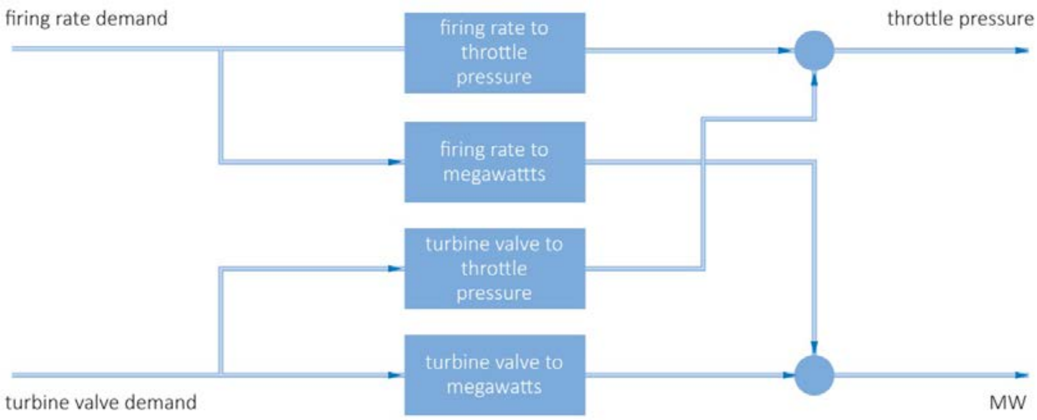

Figure 4 An example of two interacting control loops (EPRI, 1998)

One strategy in advanced control is attempting to automate the complex control actions made by human operators, essentially employing forms of artificial intelligence. This has led to the development of techniques such as fuzzy logic and expert systems. However, the most common approach to dealing with complex multivariable systems is to develop a mathematical model of the process, giving rise to the term model-based optimisation. Rather than building the process model from a highly demanding first-principles analysis of the system, it is usually much easier to create an empirical model using operational data from the plant. This process of 'system identification' can draw on a range of mathematical techniques including state space models and neural networks. The principal challenges for developing an accurate plant model are the need to account for non-linearity and dynamics in the system, both of which feature heavily in power plant control. The need for a dynamical treatment arises as the power plant may rarely be at steady-state, with control actions requiring an, often significant, delay before the final system response is observed. The technique known as model-predictive control has become almost synonymous with APC, owing to its effective incorporation of this time-dependent element, and is widely used throughout the process industry. However, the relative difficulty of incorporating non-linearity into MPC models has led to the ongoing use of non-linear system approximators such as neural networks and fuzzy logic.

Lastly, as power plants grow in size and complexity and system models are more challenging to develop, new model-free approaches are emerging based on techniques from adaptive control.

3.1 Artificial intelligence

3.1.1 Fuzzy logic

One of the earliest forms of advanced control to be used in process plant, fuzzy logic is a means of mimicking the decisions of human operators with a computational process. Experienced power plant operators effectively carry out forms of multivariable and non-linear control through actions such as adjusting one variable whilst keeping an eye on another, or applying vague rules such as 'increase cooling water when temperature is high and rising'. Fuzzy logic provides a mathematical treatment of these kinds of linguistic-based rules which deal with imprecise categories, allowing an automated process which generates precise control actions. Although derived from simple rules, the resulting control algorithms are often highly complex, non-linear, and multivariant. However, the advantage of fuzzy logic is that their basis in linguistic rules makes them more easily understandable to plant operators, and better able to use human experience in their design (Basu and Debnath, 2015).

Fuzzy logic is fundamentally based on the use of function known as membership sets, which enable precise input values to be placed in linguistic sets in a process called 'fuzzification'. Membership sets are functions of the variable designed to approximate vague linguistic categories. For example, 'very hot' and 'extremely hot' could be expressed using square and cubic functions respectively. Precise input values of temperature will fall within several categories with a 'degree of membership' according to the value of each function (Figure 5). A rule base dictates appropriate control actions for each membership set, converting them to output sets whose degree of membership dictates the weighting or 'firing level' of the control action. A process of 'defuzzification', which may simply be multiplying firing level by the degree of control response, is then used to convert the control actions and their firing levels to precise output values.

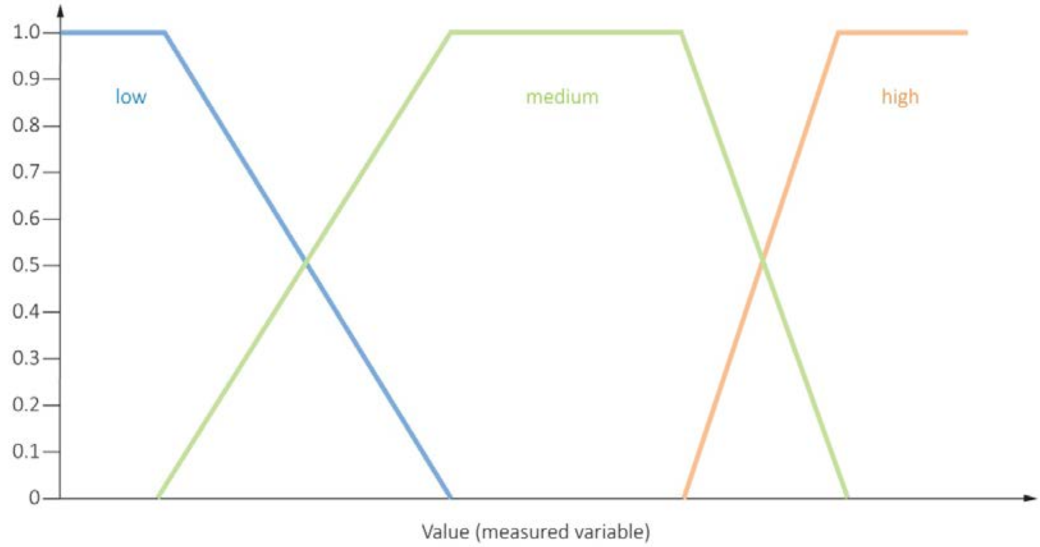

Figure 5 Example of fuzzy logic membership sets

As a simple example, an input pressure value will have varying degrees of membership in 'low pressure', 'high pressure', and 'medium pressure' sets. Using the rule base, these are converted to degrees of membership in associated output sets such as 'raise pressure', 'maintain pressure', and 'reduce pressure'. The final control action will be the combination of each of these control responses weighted by their membership such as 10% raise pressure, 30% maintain pressure, and 60% reduce pressure.

Fuzzy logic can be used in combination with neural networks to form so-called fuzzy networks (Barros Vieira and others, 2003).

3.1.2 Expert systems

Expert systems or expert rules are also a means of codifying engineer knowledge and operator experience into automated control actions. Like fuzzy logic, they employ rule bases and an inference engine to convert rules into precise control actions. However, they are capable of more advanced reasoning such as refraction (recently activated rules are not considered) and recency (priority is given to recently applied rules). In effect, the inference engine provides a way of prioritising discrete control actions, or rules, for a given set of conditions (*see* Section 4.3.1). They can be integrated with model-based optimisation techniques, for example, providing a useful means of dealing with discrete changes such as switching between models (James and Spinney, 2011; Basu and Debnath, 2015; Mayadevi and others, 2014; Tzfestas, 2009).

3.2 Model-based optimisation

In a general sense, model-based optimisation techniques use some mathematical model to represent the relationships between process variables, and an optimisation or cost function which can be minimised to find the optimum system state for a given set of disturbance variables. Possible forms of model include sets of linear differential equations such as state spaces, or non-linear algorithms such as neural networks. The model is usually optimised using search algorithms designed to locate minima in functions, such as gradient descent, direct search, or genetic algorithms. The direct search algorithm is useful in optimisation problems as it can be used with unknown functions: an iterative search is performed of the function, at each step searching surrounding points and moving to the one which is lower than the current point (Kumar, 2012). Also suitable for unknown functions, biomimetic approaches to optimisation such as evolutionary algorithms and 'ant colony optimisation' are attracting growing interest.

The empirical models used in this form of control require a process of system identification, in which they are trained on relevant plant data. This can include historical data from standard closed loop control, but may also require manual open loop tests which explore more various combinations of process variables. Once operational, the model continues to learn and improve based on the results produced by its own control actions.

3.2.1 Neural networks

Neural networks are highly nonlinear algorithms which can be used to approximate unknown complex functions when 'trained' on sufficient input and output data from the function. Their interconnected structure and ability to adapt and 'learn' in this manner has given rise to the eponymous analogy to the unique processing capabilities of the networks of biological neurons which make up the brain. The ability to model functions which have lots of training data available makes them obvious candidates for modelling complex process systems, and they have been extensively used for this purpose, particularly prior to the recent rapid growth in predictive methods (Spring, 2009).

In an artificial network, one 'neuron' is some non-linear function, commonly a log-sigmoid function, which takes several inputs and is weighted by adjustable parameters. Several of these neurons can be combined in a 'layer', in which all input values are separately weighted and fed to every neuron in the layer. Each neuron in the layer generates one output, which can in turn be passed to a second layer of neurons in a multi-layer network. With appropriate functions in each layer, two layer networks can be used as a universal approximator of any function (Hagan and others, 2002). Neurons between the input and output layers are sometimes referred to as 'hidden layers'.

Training of neural networks is essentially a procedure for selecting the network weightings which best approximate the function of interest, or the process model. Figure 6 shows training by backpropagation, where the error between the neural network output and the process history value is fed back to the network to adjust its parameters. Pursuing variations in the weightings which reduce the error allow the network to be optimised according to the method of gradient descent (Hagan and others, 2002; Piche and Bartlett, 2008).

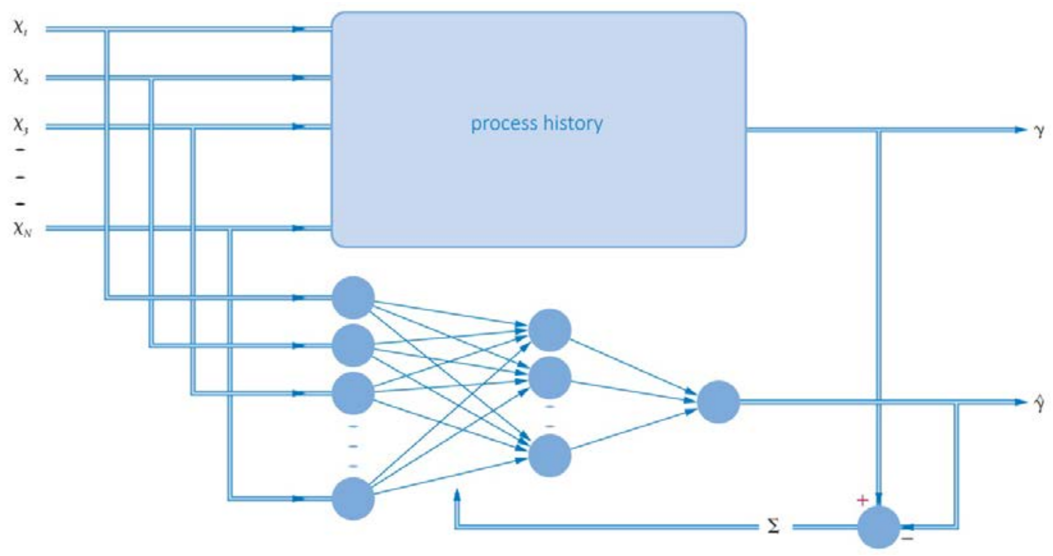

Figure 6 Training a neural network by backpropagation. Weights are adjusted to minimise model error (Piche and Bartlett, 2008)

Model-based optimisation using neural networks benefits from accurate approximation of non-linear relationships, but it is much more challenging to generate dynamic neural models, and in practice they are rarely applied in this way. Consequently, advanced process control systems may reserve neural networks for steady-state optimisation of slow changing variables, and employ a dynamic model such as MPC for less stable variables such as steam temperature (James and Spinney, 2011). A neural network model can also adapt and improve as it gains operating experience with the plant.

Besides their use in system identification, neural networks can be used directly in controllers as a means of simulating the appropriate function required to minimise set point error (*see* Section 3.3).

3.2.2 Model predictive control

MPC has seen enormous success in process industries since the 1980s and increasingly rapid adoption by the power industry over the last decade. With the use of dynamic process models, MPC is able to anticipate the future effects of multivariable control actions and modify them accordingly, rather than merely optimising the process based on its current state. This allows the control system to account for delays in the process response and deal with significant dynamic interaction between variables. MPC is also highly effective at incorporating process constraints (operating limits imposed on variables) as they can be represented explicitly in the optimisation problem (EPRI, 1998; Kramer and others, 2006; Koelsch, 2013; Immonen, 2009; Edlund and others, 2008).

MPC usually relies on linear, dynamic models obtained empirically from process data, although physical models are also possible. In commercial MPC, these dynamic models are usually based on state spaces, step response, or transfer functions. Simplifying the process as linear models allows the summation of independent variables and therefore the use of direct matrix algebra for prediction variable response. A linear approximation is often sufficiently accurate as even non-linear processes can be considered linear over a restricted operating range. Several approaches can be used to compensate for the lack of non-linearity in the model, including a corrective feedback mechanism in the model, or transformation of the process variables before they are used in the model. When non-linear models are used, they are often linearised before use in MPC.

The dynamic model is used to explore possible trajectories of the current plant state until a future time, which could be around one hour for a combustion optimisation process (Kramer and others, 2006). An optimisation cost function, which expresses the output targets and system constraints, is then minimised using a numerical algorithm to find the best possible series of control actions over the duration of the prediction (Figure 7). However, only the first step of this control plan is actually implemented on the plant, with the model instead sampling the plant state again and repeating its prediction up to a new future time. This process of continually pushing back the prediction time has led to the common description of MPC as a receding horizon technique.

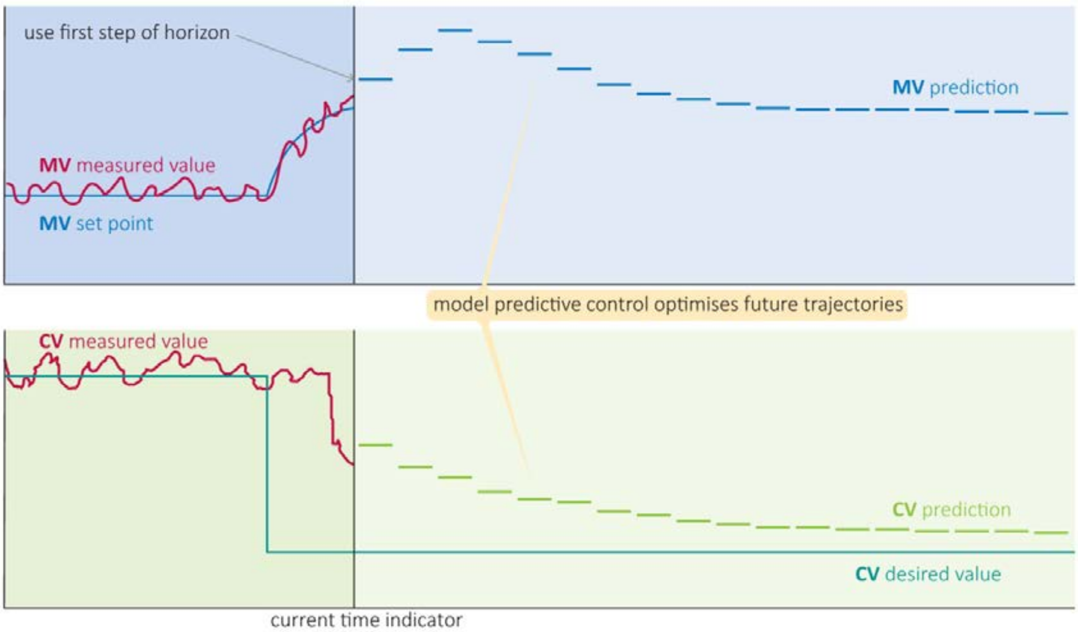

Figure 7 Illustration of model predictive control (MV, manipulated variable; CV, controlled variable) (James, 2011)

MPC is a highly active research area in advanced control, with research goals including the development of adaptive MPC mechanisms, non-linear dynamic models such as neural networks, and techniques using physical-models (Priyadarshani and others, 2012; Vincent and others, 2009)

3.3 Model-free adaptive control

Model-free adaptive control (MFAC) is an alternative approach to advanced control which is well-suited to systems which are difficult to model. In contrast to traditional adaptive control, which automatically adjusts the gains of a PID controller, MFAC replaces the PID controller with a neural network which is continuously updated to minimise the set point error (Cybosoft, 2015; Cheng, 2005; Huo and Jin, 2014; Zhang and others, 2013). This kind of controller can also be known as a direct neural controller, as opposed to the indirect use of neural networks in system identification.

MFAC is intended to serve as an effective and versatile compromise between the general purpose nature of PID controllers and the highly system-specific solution provided by model-based optimisation. The system identification process used to develop plant models often requires open loop tests to acquire a range of process data which can be time consuming and unpopular with plant operators. As power systems become increasingly complex, producing accurate models, whether empirical or physical, may also become too challenging. On the other hand, advanced control problems are generally beyond the capabilities of basic PID controllers, and they require frequent operator tuning.

A MFA controller such as the one depicted in Figure 8 is based on a neural network called a multilayer perceptron, comprising an input layer, one hidden layer with N neurons, and an output layer with one neuron. The set point error in the controlled process is fed to the input layer, and weighting factors within the network are adjusted to find the value of the manipulated process variable which minimises the error. As for system models, the optimisation process is carried out using a numerical search algorithm. MFA controllers for non-linear processes can incorporate an additional ‘process non-linearity factor’.

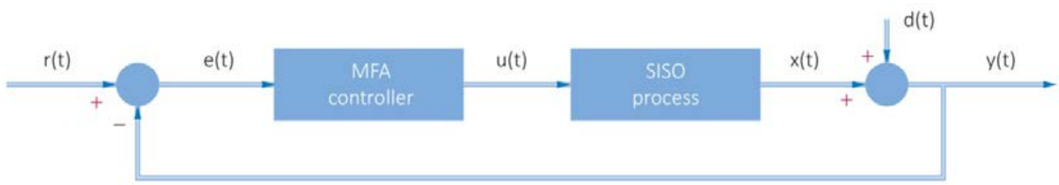

Figure 8 A single loop model-free adaptive control system, where y(t) is the process variable, r(t) the set point, e(t) the set point error, u(t) the control action generated by the MFA neural network, and d(t) are system disturbances (Cheng, 2005)

4 Combustion optimisation

There is increasing pressure on coal plant to operate at high efficiency and with reduced NOx emissions, but meeting both these goals simultaneously requires a delicate balance to be maintained in the furnace. Whilst sufficient excess air must be fed to the furnace to achieve complete coal combustion, too much air has the undesirable side-effect of promoting NOx formation as more oxygen becomes available in the high temperature region of the flame. Raising the amount of excess air also lowers overall plant efficiency, as the increased volume of air flowing through the boiler leads to increased fan power consumption and greater heat losses with the larger volume of flue gas. On the other hand, operating with very low levels of excess air also carries a risk of increased tube wastage associated with reducing conditions in the furnace. As a result, boilers tend to be operated in a 'comfort zone' of excessive excess air in order to ensure complete combustion and longer material lifetimes, at the expense of unnecessarily high NOx emissions which can often require downstream abatement (Figure 9). At the same time, the effect of fuel-air stoichiometry on furnace temperatures, which in turn affect slagging and steam temperatures, must also be taken into account. A trade-off between lower emissions and increased steam temperatures may be necessary, although excessive steam temperatures which need attemperating also represent an efficiency penalty (Table 3).

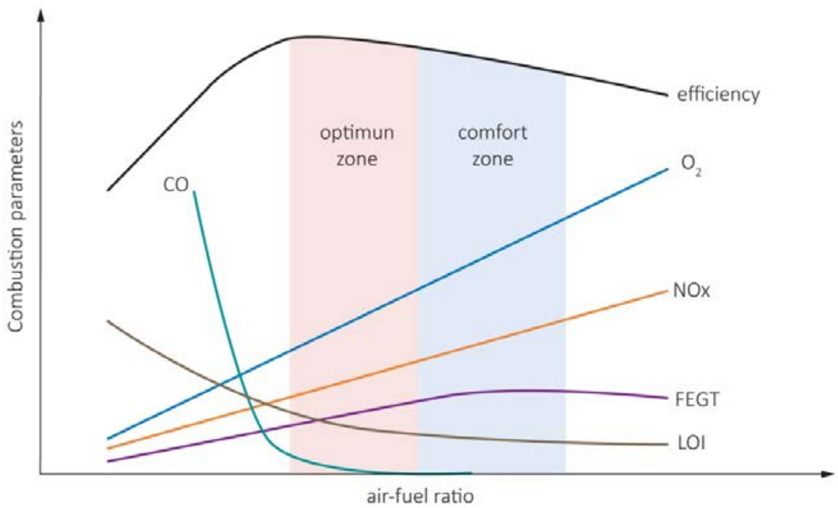

Figure 9 The variation of key combustion parameters with air-fuel ratio, showing the potential efficiency and emissions improvements achievable with optimised combustion (Widmer and Marquez, 2012)

Table 3 Heat rate gains derived from aspects of improved combustion (Prakash, 2013)

Parameter	Deviation	Effect on heat rate
Excess air (O_2)	per %	7.4 kcal/kWh
Exit gas temperature	per °C	1.2 kcal/kWh
Unburnt carbon	per %	10–15 kcal/kWh
Coal moisture	per %	2–3 kcal/kWh
Boiler efficiency	per %	25 kcal/KWh

However, maintaining the air-fuel ratio in the narrow optimum zone can be particularly challenging for large multiburner furnaces subjected to frequent load changes, where localised areas or transient periods of poor combustion can occur. Even if an ideal overall air-to-fuel ratio is achieved in the furnace, imperfections in the distribution of air and coal between individual burners can frequently lead to an 'imbalanced' furnace with locally air-deficient regions. This challenge is usually compounded by a relative sparsity of accurate, online monitoring of the relevant furnace parameters such as temperature and gas concentrations, providing an incomplete picture of how the process responds to inputs. Two complementary approaches can therefore be considered for achieving closer control of combustion: either improving the range and accuracy of sensory information available from the boiler, or using advanced control systems which are able to identify the complex relationships between boiler variables and the optimum input settings for any given situation. The large number of interrelated variables and the delicate balance of outputs required in combustion optimisation have led to it becoming the first aspect of plant control to benefit from the introduction of truly advanced process control techniques, with often dramatic efficiency and emissions improvements allowing for rapid payback times (Spring, 2009). Meanwhile, developments in sensor technologies have allowed the variation in combustion parameters to be mapped across a furnace cross-section rather than just taken at select points, as well as enabling online monitoring of coal and air flow into the furnace.

4.1 Sensors used in combustion optimisation

The combustion process can be monitored and controlled both via its reactants, in the form of coal and air flow measurement, or its products, through flue gas and ash analysis. In addition, optical and spectral analysis of the coal flame can be regarded as a means of monitoring the combustion reaction itself. Many coal plants rely on only a limited number of sensors for combustion control, providing signals which can be either overly global, such as total coal and air feedrate, or overly localised, such as measurements of furnace exit gas temperature or excess oxygen at only one location. More precise measurements of coal flow rates to individual burners or CO distribution in the boiler may only monitored by occasional sample measurements, with future control actions made on the basis that these readings will remain valid over the operating range of the plant. In order to achieve fully optimised combustion down to the level of individual burners, coal plants are installing increasing numbers of online sensors, which are able to constantly relay useful control signals from all stages of the combustion process.

Analysis of flue gas composition for combustion control purposes poses distinct challenges from the analysis performed by continuous emissions monitoring systems (CEMS) at the stack. CEMS usually employ complex extractive analysers which remove a flue gas sample from the duct and use a series of individual gas sensor modules or a more advanced spectroscopic technique such as Fourier transform infrared (FTIR) spectroscopy to determine the composition. These sensitive analytical techniques require sample conditioning to avoid acidic condensation in the instrument, such as dilution with clean air, cooling to remove moisture, or heating the entire apparatus to above the dew point. Although stack measurements can be used in combustion control, it is preferable to analyse flue gas as close to the combustion process as possible and at multiple locations in order to detect imbalances across the furnace. Together with the need for faster response times, this favours the use of cheap, simpler extractive analysers which perform little sample conditioning or preferably, measurements taken in the flue gas without the delay imposed by sample extraction. Such in situ analysis can take the form of sensors placed directly in the flue gas, or 'line-of-sight' optical absorption measurements in which a transmitter and receiver are placed either side of the duct or furnace and a path through the flue gas is analysed.

4.1.1 Oxygen

Measurement of the oxygen concentration remaining after combustion is used as a feedback signal for the proportion of excess air used and is therefore an essential variable in combustion control. By controlling the intake and distribution of combustion air, this oxygen signal is regulated to an oxygen set point which may require adjustment with changes in firing rate or other disturbances. Lowering the oxygen set point whilst avoiding the onset of incomplete combustion is a key means of optimising combustion for higher efficiency and reduced NOx emissions.

Whilst a number of technologies exist for oxygen sensing, by far the most widespread in coal furnaces is the electrochemical zirconia-based sensor. In this device, zirconia is used as an oxygen ion-conducting solid electrolyte, placed between the sample gas and air as a reference. The electrolyte is coated with catalytic platinum electrodes on which oxygen on both sides absorbs and dissociates into ions and electrons, producing a voltage which is proportional to the oxygen concentration gradient across the cell (Simmers, 2010; Dynacer, 2015) (Figure 10). For the ionic conduction process to take place, the sensor must be maintained at temperatures over 300°C, and a dedicated electric heater is usually employed to maintain the zirconia in the range of 700°C to 750°C.

Zirconia sensors are truly in situ devices which can be placed directly in the flue gas on the end of probes, protected from the high temperatures and fly ash by a stainless steel or ceramic casing and a filter through which the flue gas diffuses. With the use of temperature-resistant ceramic shielding they have even been designed to withstand temperatures of up to 1400°C suitable for higher temperature regions of the furnace (Rosemount, 2009). These high temperature oxygen sensors from Rosemount also dispense with the heater, relying on ambient heat alone. Current research into this type of device is described in Section 6.1.1, including the use of a sealed metallic reference in the place of air to enable drift-free measurements.

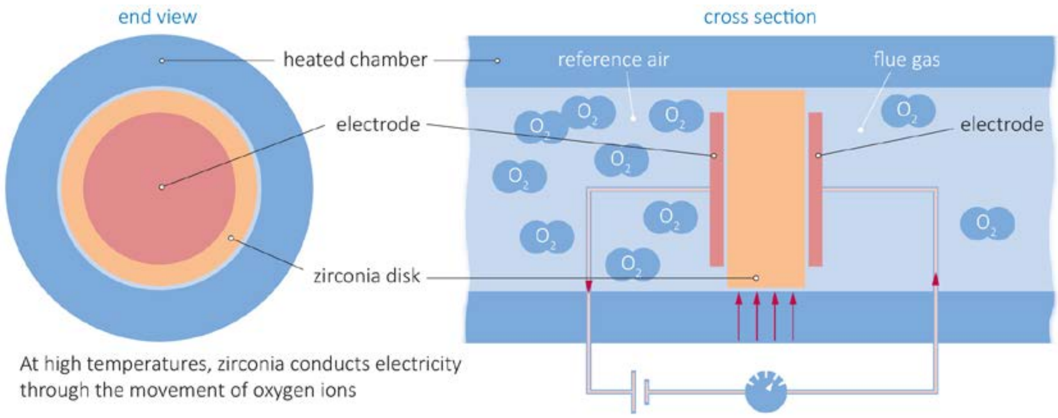

Figure 10 A schematic of a typical zirconia-based oxygen sensor (Servomex, 2006)

A key advantage of zirconia sensors is the inverse, logarithmic response which actually improves in accuracy as oxygen concentration decreases and is therefore a good match for the low oxygen levels remaining after combustion (Simmers, 2010). However, only one or few sensors are commonly employed in coal boilers, usually located between the economiser and air preheater where temperatures are around 300–400°C. This point is close enough to the furnace for combustion control, but far enough to avoid slag build-up on the probe or require the use of high temperature materials. However, air ingress in the convective pass can artificially raise oxygen levels, and distinctions between the flue gases generated by individual burners may be difficult to resolve. A common challenge to optimising the oxygen set point is therefore incomplete knowledge of the true levels of oxygen in the furnace due to overly localised measurement.

Extractive oxygen analysers may also employ zirconia sensors, but paramagnetic analysers, which exploit the fact that oxygen is attracted by a magnetic field, are also widely used for this purpose (ABB, 2013; Siemens, 2011). The flue gas sample is introduced to a strong magnetic field, where the movement of oxygen may be detected in several ways, including with flow sensors or by the torque exerted on a pair of rotating, nitrogen-filled glass spheres (Servomex, 2015; Yokogawa, 2009). An advantage of this kind of measurement is that it is not affected by the presence of combustible gases, which artificially reduce the signal in zirconia sensors by reacting with oxygen. However, the need for a gas sampling system introduces complexity and reduces response time.

4.1.2 CO

As the most sensitive and accurate indicator of incomplete combustion, CO concentration in flue gases can act as a highly useful control variable within the furnace, and is ideally kept below 200 ppm (Simmers, 2010). Detection of an unacceptable increase in CO levels, or CO 'breakthrough', can be used to trim the excess oxygen set point to an appropriate level and adjust the excess air accordingly. Alternatively, a more sensitive CO measurement can itself be used as a control variable for the furnace, particularly in optimising the oxygen set point.

CO sensing in coal furnaces is generally based on two fundamental techniques: infra-red absorption or electronic sensors using catalytic combustion. The latter category employs a conductive element coated with a combustion-promoting catalyst such as platinum. As CO and other combustibles (usually minimal relative to CO in coal boilers) are oxidised on the catalyst, the conductive element is heated, raising its resistance (Yokogawa, 2008). Catalytic bead sensors, in which a conductive filament is coated with a bead of catalyst, are the most common implementation of this principle, used in devices from GE, ABB, and Emerson/Rosemount. Too sensitive to be placed in situ, these devices require sample extraction but can be 'close coupled', in which sample conditioning consists only of particulate filtration (ABB, 2006a; GE, 2012). A weakness of catalytic bead sensors in coal plant applications is their vulnerability to catalyst poisoning by SO_2, although the Rosemount sensor claims sulphur resistance. In an alternative use of the catalytic combustion principle, Servomex produce a thick film thermistor which consists of thin conductive tracks deposited on a ceramic substrate and coated with a layer of CO-sensitive catalyst. This design claims high accuracy and resistance to catalyst poisoning, and is also applied in a close coupled configuration (Servomex, 2006).

IR analysis of the flue gas CO content can be extractive, in which flue gas is removed from the furnace to a sample cell for analysis, or in situ, where an IR source and detector are placed either side of the flue gas duct and the entire flue gas volume acts as a sample cell. In situ devices from Rosemount and SICK makes use of gas filter correlation, where a portion of the detected beam passes through a vessel of pure CO, saturating the CO absorption signal and provides a baseline for interfering absorption from other species (Rosemount, 2010; SICK, 2013a). Although these line-of-sight measurements provide a useful average over a whole section of the furnace, they are sensitive to high levels of particulates or temperatures much greater than 600°C. Thermal expansion and vibration can also disrupt the alignment of the source and receiver, requiring signal filtering, and there is no practical means of calibrating the measurement. Alignment issues can be mitigated by use of a dual-pass configuration, where a furnace probe is used to reflect the beam back to a combined source and detector unit. A more recent innovation in line-of-sight IR is the use of tunable diode lasers as the source, which allows higher accuracy and monitoring in high temperature locations (*see* Section 4.1.6).

Extractive IR analysis is usually based on a non-dispersive IR sensor, which uses a single detector at the peak CO absorption frequency to determine changes in CO concentration of a flue gas sample (Ferri, 2015). As the IR absorption of water interferes with this measurement, NDIR sensors are 'dry' extractive devices which condense out flue gas moisture prior to analysis and thus suffer from some lag time. However, IR analysis generally provides a more sensitive measurement than catalysis-based sensors, and can easily be integrated with SO_2 analysis by addition of another IR detector (Simmers, 2010).

4.1.3 NOx

The levels of NOx in flue gas are monitored at the stack as part of CEMS, and also at the inlet and outlet of selective catalytic reduction (SCR) units for NOx abatement in order to regulate reagent dosage and detect degradation of the catalytic bed. The most common form of NOx sensor for either purpose are chemiluminescence detectors (CLD), which exploit the fact that NO emits light when it reacts with ozone. A stoichiometric excess of ozone, generated in the device by UV irradiation of oxygen, is introduced into a reaction chamber with a controlled volume of flue gas, and light from the resulting reaction is detected by a photomultiplier tube or photodiode. The intensity of the emitted light can then be related to the NO concentration. NO is the principal component of pulverised coal NOx and its measurement may suffice for combustion optimisation purposes. However, detection of total NOx can be achieved by reducing NO_2 to NO though heating the sample in a vitreous carbon bed prior to analysis (Rosemount, 2008). CLD sensors are usually extractive and require sample drying, but a close coupled configuration from Brand Gaus mounts the reaction chamber on a probe directly in the flue gas, using a low flow rate sampling and drying system (Brand Gaus, 2004).

The most common alternative method for NOx analysis is ultraviolet (UV) photometry, which measures the absorption of UV light by a flue gas sample. As NO and NO_2 both show distinct absorption peaks in this region of the spectrum they can be detected separately, and an SO_2 or NH_3 measurement may also be incorporated in some instruments. The flue gas sample may also be analysed without water removal, as water does not absorb in the UV (ABB, 2009a). More accurate UV analysis, avoiding interference from other gases, can be achieved by taking a broad UV spectrum rather than measuring absorption at specific wavelengths. Such UV spectroscopy can also be performed as a line-of-sight measurement across the duct (SICK, 2013b).

Lastly, it is possible to measure NOx concentration using a zirconia-based electrochemical cell similar to those used for oxygen detection. This technique has been commercialised by Horiba and has seen use for in situ devices for SCR control. However, the structure and operating principle of the device is more complex than the oxygen device; zirconia-based and other solid-state NOx sensors are discussed in Section 6.1.1.

4.1.4 Gas sensor arrays

Flue gas in the convective pass remains relatively 'stratified' as individual columns emitted by each burner, so localised regions of high CO originating from individual burners may still be present even at the economiser exit. Analysis of flue gas at a single location is therefore unrepresentative of the overall composition, and inadequate for identifying poorly operating burners and balancing combustion over the furnace. To obtain a more detailed picture of CO and oxygen distribution in the back pass, a grid of flue gas probes can be deployed (Figure 11). These are usually extractive probes which analyse a flue gas sample in a compact, robust unit for key components.

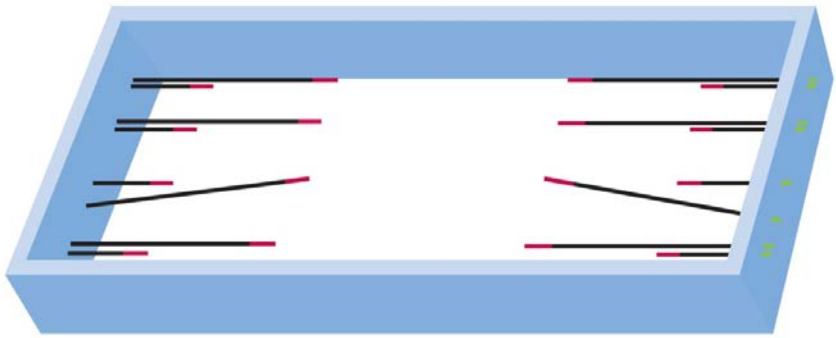

Figure 11 The grid placement of O_2/CO sensors in Delta CCM (Ferri, 2015)

Although no longer sold, the Zonal™ system from GE was notable for employing a grid of six to 24 probes for CO and oxygen analysis across a relatively high temperature region at the top of the convective pass. This location was chosen as the best point at which to capture the variation in flue gas composition due to individual burners. The close coupled probes take undried flue gas sample to a heated zirconia cell for oxygen analysis and a catalytic bead CO sensor. The data gathered by these sensors is analysed by a tuning system able to model the relationship between burners and sensors, and compiled into optimised set points for real-time adjustments to the boiler (Widmer, 2009; Widmer and others, 2009; Widmer and Marquez, 2012).

The continuous combustion management (CCM) system from Delta deploys a grid of extractive probes in the economiser region of the boiler which use NDIR and a zirconia cell for CO and oxygen measurement respectively (Ferri, 2015). A thermocouple in the probe head provides a simultaneous temperature measurement. The probes are themselves a patented design which take in a flue gas slip stream via the Venturi effect. Moisture in the flue gas sample is condensed by a Peltier cooler before further removal by an adsorption in a polymer membrane. An additional CLD for NO measurement has recently been added to the analysis module, with SO_2 detection also planned for the system. CCM is promoted as a cheaper alternative to TDLAS systems (*see* Section 4.1.6) which also avoids the problems with SO_2 encountered by catalytic bead sensors. In 2010, CCM was installed on a 770 MW at Crystal River Power Plant in Florida in combination with coal and air flow monitoring systems, enabling the oxygen set point to be reduced to 2% and an associated 0.5% gain in boiler efficiency (Estrada and Sisson, 2011)

4.1.5 Temperature

The temperature of the flue gas on exiting the radiative section of the furnace before entering the convective pass, or furnace exit gas temperature (FEGT), is the primary temperature variable used in furnace control (Jethra, 2013). The FEGT is carefully monitored to ensure heat transfer is properly balanced between the two sections of the boiler, and that temperatures are kept below levels at which excessive slagging or superheater material failure could occur. As the delayed combustion promoted by low NOx firing can result in high FEGT, it is also an important means of keeping such practices within safe limits. The traditional method of measuring FEGT by sampling with a water-cooled high velocity thermocouple is unsuitable for optimised low NOx coal combustion, which requires some form of online monitoring. The principal sensor candidates for this purpose are instead infra-red or acoustic pyrometry. IR pyrometers exploit the presence of large concentrations of CO_2 in combustion flue gases, the strong IR emission of which can be correlated to the gas temperature via the Stefan-Boltzmann law. Lumaspection™ IR pyrometers from Lumasense focus on a spot in the flue gases of several millimetres in diameter and can measure temperatures from 400°C to 2000°C (Lumasense, 2013). EUtech's EUflame system uses an array of several pyrometers installed around the boiler to provide a complete temperature profile across an entire furnace cross-section, usually either at the furnace exit or burner level. In addition to gas temperatures, this system is also able to extract particulate loading and temperature from the emissivity data, which can in turn be used to derive the coal burn rate (EUtech, 2015).

Acoustic pyrometers send sound waves across the furnace and use the fact that the speed of sound depends on gas temperature. Enertechnix produce an acoustic pyrometry system which also uses multiple transmitters and receivers positioned around the boiler walls to generate a cross-section of the temperature distribution (Enertechnix, 2013). A drawback to acoustic methods is that the speed of sound depends greatly on the gas composition, and can also be interfered with by soot particles and the refraction of the sound wave front by density and temperature gradients (Babcock and Wilcox, 2005). On the other hand, the acoustic detectors themselves have much less stringent requirements for cleaning than their optical counterparts.

Systems which are able to generate 2D temperature profiles in this manner can be effectively utilised in furnace balancing, preventing material damage, and optimising selective non-catalytic reduction for NOx abatement.

4.1.6 Tunable diode laser spectroscopy

In the last decade, tunable diode laser absorption spectroscopy (TDLAS) has emerged as a useful commercial tool for detection of very low level gas concentrations in combustion flue gases. The technology employs the precise frequency lasers generated by semiconductor diodes rather than the broadband sources used in conventional flue gas infra-red analysis (Hanson, 2014). Furthermore, by adjusting the injection current to the diode the laser can be tuned in frequency, allowing it to scan either side of absorption lines of interest to accurately establish peak widths and detect gas concentrations of the order of ppb. The diodes used in TDLAS primarily produce light in the near-IR region, in which several combustion relevant species such as CO, CO_2, H_2O and CH_4 show absorption peaks (Figure 12). As this spectral region also includes the communication band used in optical fibres, the probe and detection signals can be transmitted optically between the furnace and analysis instrumentation at a remote location. Although near-IR absorption peaks are usually overtones of mid-IR peaks and consequently much weaker, this is compensated for by the high quality sources and sensitive detectors developed for telecommunications at these wavelengths.

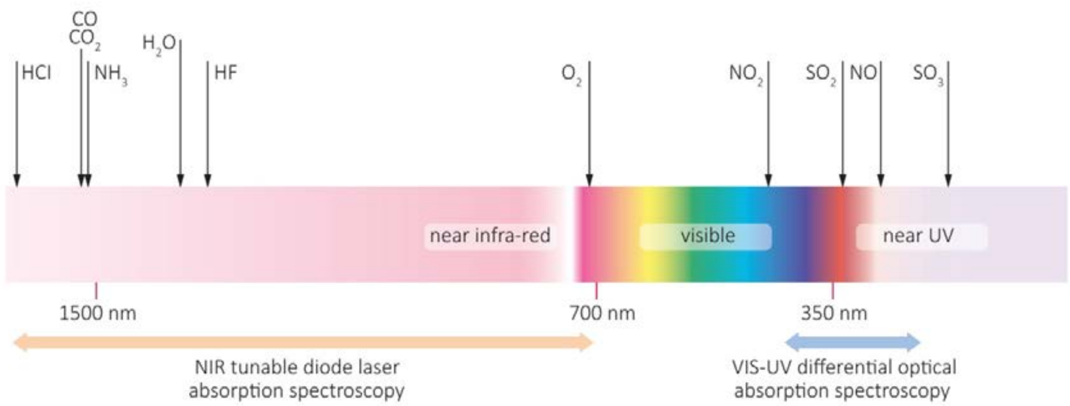

Figure 12 Spectral regions for the detection of various combustion gases, including the near IR region addressed by tunable diode laser absorption spectroscopy (Hanson, 2014)

A few TDLAS systems are commercially available for flue gas detection, including ZoloBOSS from Zolo Technologies, and TruePeak Analyser from Yokogawa (D'Hubert, 2013; Yokogawa, 2010). As for conventional line-of-sight absorption spectroscopy in boilers, these systems position a source and detector on opposing walls and take a path average measurement of gas concentrations over the entire path length. In addition to detection of several combustion gases, it is possible to accurately measure gas temperature by analysis of temperature dependent absorption peaks.

Zolo combustion optimisation by TDLAS

Currently installed on around 60 units worldwide, the ZoloBOSS system deploys a number of TDLAS source-detector pairs above the combustion zone of the furnace, essentially creating a laser grid which can map the variations in gas concentrations and temperature for that furnace cross-section (D'Hubert, 2013; Sappey and others, 2004) (Figure 13). As with grids of sensor probes, these profiles are highly useful for achieving balanced combustion and homogeneous gas concentrations over the entire furnace. Based on the pioneering TDLAS research at Stanford University, the spectroscopic method is able to measure concentrations of water, CO, O_2, and CO_2 in real-time, in addition to temperature via analysis of water absorption peaks. Emission spectrum measurements of Na and K concentrations are also possible with the same hardware, as an additional feature for monitoring corrosion risk in biomass boilers (*see* Section 4.4.2).

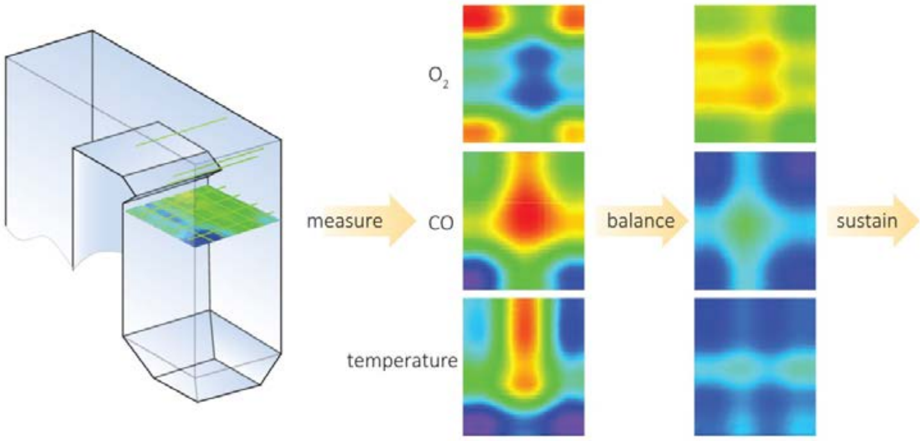

Figure 13 2D profiles of the boiler parameters generated by the ZoloBOSS system are used to balance combustion across the furnace (Stewart and others, 2012)

Key features of the system include its relatively non-intrusive nature, with laser and receiver inserted through small slots in the membrane between the boiler tubes, and the use of optical fibres to remove all processing electronics to a remote, protected area. A principal challenge of such line-of-sight systems is maintaining alignment of the transmitter and receiver during the inevitable thermal expansion and contraction of the boiler surfaces, here achieved via an automatic motorised alignment system 'SensAlign' on either side, as well as automated rods to remove slag from the device ports. As a consequence of these features, the ZoloBOSS system claims to be low maintenance and does not require calibration in the field.

ZoloBOSS aims primarily to achieve balanced combustion throughout the furnace, with resulting reductions in excess air, NOx, and CO, as well as less slagging and corrosion due to the elimination of localised hot spots and reducing conditions. In a multiburner wall-fired furnace, this constitutes using the map of O_2 and CO to identify burners which are not operating at optimum combustion efficiency, and readjusting the flow of secondary air to these burners accordingly. In a tangentially-fired furnace, the system can be used to accurately centre the fireball, preventing local excursions of superheat steam temperature and reducing slagging due to impingement of the fireball on the furnace walls. This kind of tuning can be performed diagnostically to the boiler in steady state, or integrated with dynamic control systems (Stewart and others, 2012). The temperature data generated by the system can also be used to improve intelligent soot blowing systems (*see* Section 4.3), whilst a single laser path deployed at the furnace exit can more accurately determine FEGT and help control slagging (Zolo Technologies, NDa,b).

The profile of oxygen concentrations across the furnace provided by systems like ZoloBOSS provides a means of reducing the excess oxygen set point beyond the level dictated by conventional, localised zirconia probes. Whereas a single probe can often underestimate the actual oxygen content of flue gases by over 1%pt, ZoloBOSS acts to balance oxygen levels across the furnace before lowering the oxygen set point to a more optimum level. This equates to reductions in NOx and efficiency gains associated with reducing the flow of flue gas, without the risk of creating corrosive, reducing regions in the furnace. For example, in order to reduce NOx emissions without downstream abatement equipment, 15 laser paths were installed at the 284 MW t-fired Gallatin Station in Tennessee, constituting grids in the furnace and backpass and a single path to measure FEGT. Through more accurate determination of oxygen levels in the boiler, the oxygen set point could be lowered by 0.2%pt, enabling a NOx reduction of 24% and a 1% heat rate improvement (Zolo Technologies, NDc) At the 726 MW Ottumwa Generating Station, manual balancing of the furnace with ZoloBOSS was able to reduce the oxygen set point by 0.75%pt, enabling a 2.4 MW saving in auxiliary power, a heat rate reduction of 0.9%, a 5% reduction in NOx, and 20% less CO emissions. Despite this unit previously struggling to reach target steam temperatures without causing excessive emissions, steam temperatures were actually slightly raised after optimisation. However, maintaining this performance over sustained operation of the unit required integration of the flue gas data into the unit's existing combustion optimisation software (*see* Section 4.2.1), for which results are unavailable (Martz and others, 2012).

The ZoloBOSS system can complement the advanced combustion optimisation systems described in Section 4.2, which are able to make use of the enhanced furnace data to improve their model of the complex furnace system and reduce the time needed for optimisation. Besides integration with NeuCo's CombustionOpt software at Ottumwa, ZoloBOSS has also been used in combination with both Promecon coal flow sensors (*see* Section 4.1.8) and Emerson's SmartProcess software (*see* Section 4.2.3) on a unit at Taichung Power Plant in Taiwan (Zolo Technologies, 2011). In particular, Zolo Technologies have collaborated closely with Siemens since 2007, with the furnace data generated by ZoloBOSS used to enhance Siemens' SPPA-P3000 neural network-based combustion optimisation system (see Section 4.2.5) (Starke and Williams, 2013). An early demonstration of this combined system was installed at a 720 MW unit at LaCygne power plant in Kansas City, resulting in improved combustion efficiency and reducing annual NOx emissions from 0.13 µg/J to 0.11 µg/J. In 2011, ZoloBOSS was installed together with the Siemens software at Rizhao 4, a 660 MW t-fired unit RIzhao 4 in Shandong province. The Zolo system was first used to centre the fireball and carry out parametric tests which identify key variables for use in the advanced optimiser. By using the CO signal as a control variable to optimise the oxygen set point in real time, a 0.93%pt reduction in excess oxygen was achieved, in addition to higher steam enthalpy, 14.4% less NOx at constant CO levels, and a 0.57% overall increase in unit efficiency (Thavamani and others, 2012).

4.1.7 Carbon-in-ash

Online measurement of unburnt carbon in fly ash is another effective means of detecting poor combustion efficiency and maintaining optimum combustion parameters. Low levels of residual carbon are also required for fly ash to be sold on for use in cement manufacture. Whilst laboratory analysis of fly ash samples has traditionally relied on the loss-on-ignition test, measuring the mass change after combustion of the remaining carbon, online techniques commonly use a microwave-based principle. Carbon absorbs microwave radiation and the dielectric constant of a fly ash sample is a function of its carbon content. A microwave resonance cavity filled with fly ash will therefore display a shift in resonant frequency according to its carbon content. Alternatively, the degree of attenuation and phase shift of a single frequency microwave can also be used to obtain the carbon content and total ash content respectively.

This microwave-based measurement technique has been implemented in several different forms and can be either extractive or in situ. Extractive systems can take a flue gas slipstream and separate out the fly ash using a cyclone solids separator, or divert ash collected by the particulate collection device. The fly ash fills a metal tube which acts as the microwave resonance cavity, measuring the carbon content before emptying and beginning the refilling process with a cycle time of a few minutes. (Greenbank, ND; Scantech, ND; Berthold, ND). The G-CAM system from Greenbank offers an array of up to six flue gas extraction probes across the duct between the economiser and air preheater, allowing carbon-in-ash to be profiled across the boiler as for combustion gases. Mecontrol UBC from Promecon is relatively unique in that it fixes directly to an ESP ash hopper and compacts a sample within the hopper for in situ analysis (Conrads and Prenzel, 2003). This device has been deployed at around 127 sites worldwide, including the new-build German plants Moorburg and RDK8, where it should reduce fluctuations in carbon levels resulting from frequent load changes (D'Hubert, 2015).

A sensor from ABB is able to measure the carbon content of entrained fly ash directly in the flue gas. Parabolic mirrors placed either side of the duct between the economiser and air preheater reflect microwaves of varying frequency back and forth through the flue gas, and the amplitude at the resonant frequency is used to determine the carbon content per unit volume. A separate set of electrodynamic probes is used to obtain the total fly ash loading and thus calculate the carbon percentage by mass. Measurements take place every second with an accuracy of 1%, and the microwave mirrors are automatically aligned (ABB, 2009b).

Some research is being conducted into optical techniques which could prove less sensitive to other factors such as coal rank and mineral content than microwave-based methods. Carbon content can be related to reflectance of IR light or a change in polarisation. Recent research has also correlated the spectral emittance of ash particle clusters to their carbon content (Liu and others, 2014a).

4.1.8 Coal flow

Coal flow is conventionally monitored simply by the gravimetric feedrate of coal to the pulveriser mills, which is in turn directly governed by the boiler firing rate and load demand on the plant. Distribution of the coal between burners may be checked only sporadically with sample probe measurements which are not always reliable and are not performed on separate pipes simultaneously (Sarunac and Romero, 2003; Storm, 2009). Coal is usually extracted from the coal pipe at the same rate as the air flow, whilst the actual coal flow rate will necessarily be slower (Earley and Kirkenir, 2009).

The need for improved control of individual burner stoichiometry has therefore led to increased adoption of online flow sensors on coal pipes, for which a number of suitable technologies are available. The PFMaster from ABB and Greenbank employs an electrostatic method, in which the charge developed by the flowing coal is detected by electrodes and correlated with the same measurement at a downstream sensor in order to obtain the time-of-flight between the two points and hence calculation of the coal velocity (ABB, 2006b; Coombes, 2014) (Figure 14). Together with the concentration of coal in the pipe, obtained from the total charge detected, this is used to balance coal distribution over a set of burners. The PFMaster has a rapid response time which allows detection of pulsed flow behaviour, and the electrodes sit flush with the pipe to avoid erosion. The PF-Flo from Air Monitor Corp and Mecontrol Coal from Promecon also use the cross-correlation of electrostatic signals to obtain coal velocity, but in combination with a microwave resonance technique which measures the density of coal in the pipe and thus provides an absolute value for the mass flow (Air Monitor Corp, 2007). Installation of Mecontrol Coal sensors on burner pipes at the 265 MW Stigsnaes Power Plant in Denmark enabled the furnace to be balanced and tuned, resulting in a 30% reduction in oxygen set point, 44% less NOx, and a 1.3 %pt efficiency increase (Olsen, 2008).

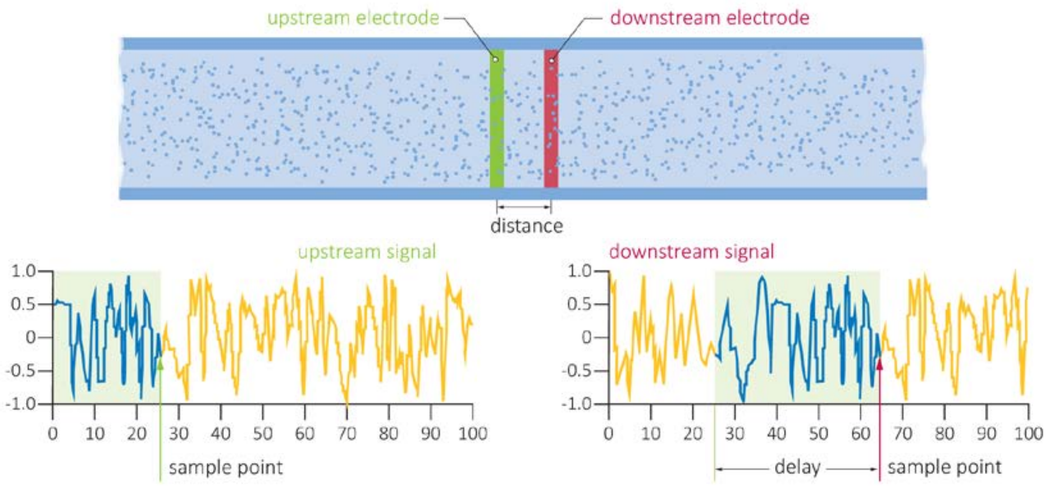

Figure 14 Measurement of coal flow by cross-correlation of electrostatic charge signals (Coombes, 2014)

Other commercial devices, including EUcoalflow from EUtech and Coal Flow Analyzer from MIC, employ higher frequency microwave signals to determine coal flow rate. Using two or three unintrusive microwave transceivers placed around the circumference of a pipe, the time-dependent intensity of microwaves reflected from the moving coal particles can be related to an absolute mass flow rate (Turoni, 2012). As part of EUtech's overall air-fuel ratio optimisation strategy, these sensors claim to enable efficiency improvements of 0.3 to 1%, in addition to reductions in emissions and slagging (*see* Section 4.2.6).

More recently, the increasing availability of digital imaging systems has allowed optical imaging-based techniques to challenge existing methods, as they are non-intrusive and less affected by environmental factors such as temperature, humidity, and other sources of charge (Roberts and others, 2007). Such systems employ CCD digital video cameras to film coal particles illuminated by high power LEDs, obtaining particle concentration along with particle velocity from the degree of blur in the images. However, the transparent window required in the coal pipe can become obscured by deposits unless some cleaning system is employed.

4.1.9 Air flow

The flow rate of combustion air to the furnace is a key parameter in control of the combustion process, whilst the flow of primary air to the pulveriser mills must also be kept within an optimum range which maintains coal suspension but minimises erosion and NOx formation. Both these air flows are typically monitored using Venturi flow meters, which measure the reduction in fluid pressure when flowing through a constricted section of pipe, or Pitot tubes, which measure the pressure built up by the air when brought to rest (Air Monitor Corp, 2015). Pitot tubes can be even be fitted to each combustion air compartment of burners, as in Air Monitor Corporation's individual burner air monitor (IBAM) system. More complex designs such as Fechheimer Pitot tubes or flow straightening devices may be necessary to account for the non-axial flow components of turbulent air, commonly encountered in short or contorted sections of duct (Air Monitor Corp, Rosemount). In dirty air, Pitot tubes and Venturis also require self-purging mechanisms to dislodge accumulated particulates. These enhancements are particularly necessary for measuring the flow of primary air which can contain fly ash introduced by regenerative heaters and often lacks long sections of duct with straight flow. The velocity of entrained particulates can also be used as a proxy for the air flow, with the charge signals developed by these particles used to obtain their velocity in the same fashion as for coal flow (Promecon, ND).

Both Venturis and Pitot tubes are volume flow meters which need accompanying measurements of temperature and pressure to obtain air density, and thus the more useful value of total mass flow. Inhomegeneities in temperature, such as following attemperation of primary air, can therefore introduce inaccuracies. Thermal mass flow meters are an alternative which provide the mass flow directly, based on the measuring the extent of the convective cooling effect by the flowing air on a heated element (Kurz Instruments, ND; Yoder, 2013). These have the additional advantages of improved accuracy at low flows compared to Pitot tubes, and not introducing energy costly pressure drops to the duct as with Venturis. Although early thermal anemometers tended to suffer from fouling which alters the rate of heat dissipation, newer designs such as thermal mass insertion meters developed by Kurz Instruments avoid this by operating at much higher temperatures than the surrounding air.

As for coal flow monitoring, optical flow meters are an emerging technology with the advantage of being non-intrusive and less sensitive to environmental factors (Optical Scientific, 2015). They can exploit the phenomenon of optical scintillation, in which light is refracted by localised variations in temperature and density of the air.

An alternative approach to determining air flow at the burner level is to calculate the expected value by combining available flow measurements with a physical model of air flow through the system. Known as a 'soft sensor', this is the strategy employed by EUtech's 'EUsoft air', which can essentially monitor air flow at all points in the plant's hydraulic network and responds to changing inputs such as damper position. The soft sensor data are generated in real time by a powerful PLC and sent to the DCS (EUtech, 2015).

4.1.10 Flame detectors

As maintaining a stable, well-attached flame is essential for safe pulverised coal combustion, optical flame detectors are installed on each burner. These typically measure the amplitude and frequency (known as flicker) of selected visible, IR or UV frequencies emitted by the flame, from which further analysis can yield important information on flame temperature and stoichiometry for use in combustion optimisation (Vandermeer, 1998; Fuller and others, 2004; Fireye, 2013). Some flame scanners, such as the Uvisor series from ABB, have been specially designed to provide additional information on flame quality beyond the standard requirement of monitoring the presence of a flame. Flame Doctor® from Babcock and Wilcox is a portable diagnostic system which analyses signals from a plant's existing flame scanners to identify poorly operating burners. Pattern recognition software and mathematics derived from chaos theory are used to detect characteristic deviations in flame quality and help to optimise the air-fuel ratio accordingly (Fuller and others, 2004; Babcock and Wilcox, 2009).

Video cameras can also be deployed for online imaging of the flame and, with appropriate processing software, an even greater quantity of data on flame quality and stability can be extracted from such images. Developments and current research in flame imaging techniques are discussed in Section 5.3.

4.2 Advanced process control in combustion optimisation

Advanced process control techniques were first applied to combustion optimisation in power plants in the late 1990s, and have since become widespread in the industry (Spring, 2009). In this time, combustion optimisation programs have evolved from the merely advisory role of early incarnations, to closed loop systems which continuously update the optimal control bias settings for relevant boiler variables. In a typical pulverised coal furnace, these manipulated variables include mill feeder speeds (coal flow rate), dampers controlling the flow of secondary and overfire air, and burner tilts for controlling steam temperature, in addition to set points for excess oxygen and furnace pressure (Figure 15). The optimisation system seeks to simultaneously adjust these variables to minimise controlled variables such as flue gas NOx and opacity, excess oxygen, and the water spray attemperation used to reduce excessive steam temperatures, whilst taking into account uncontrolled disturbance variables such as the load demand on the unit. Early techniques for such multivariable control relied heavily on the use of neural networks which, when trained on sufficient operational data, are capable of finding the optimum steady state combination of input variables for a given scenario. This was often combined with expert systems and fuzzy logic to introduce elements of operator experience on the plant. As computer power has increased, the use of the computationally demanding MPC has become increasingly significant, although usually in combination with other, non-linear algorithms. MPC permits dynamic modelling of the system and the ability to maintain optimised inputs throughout a load change or other disturbance.

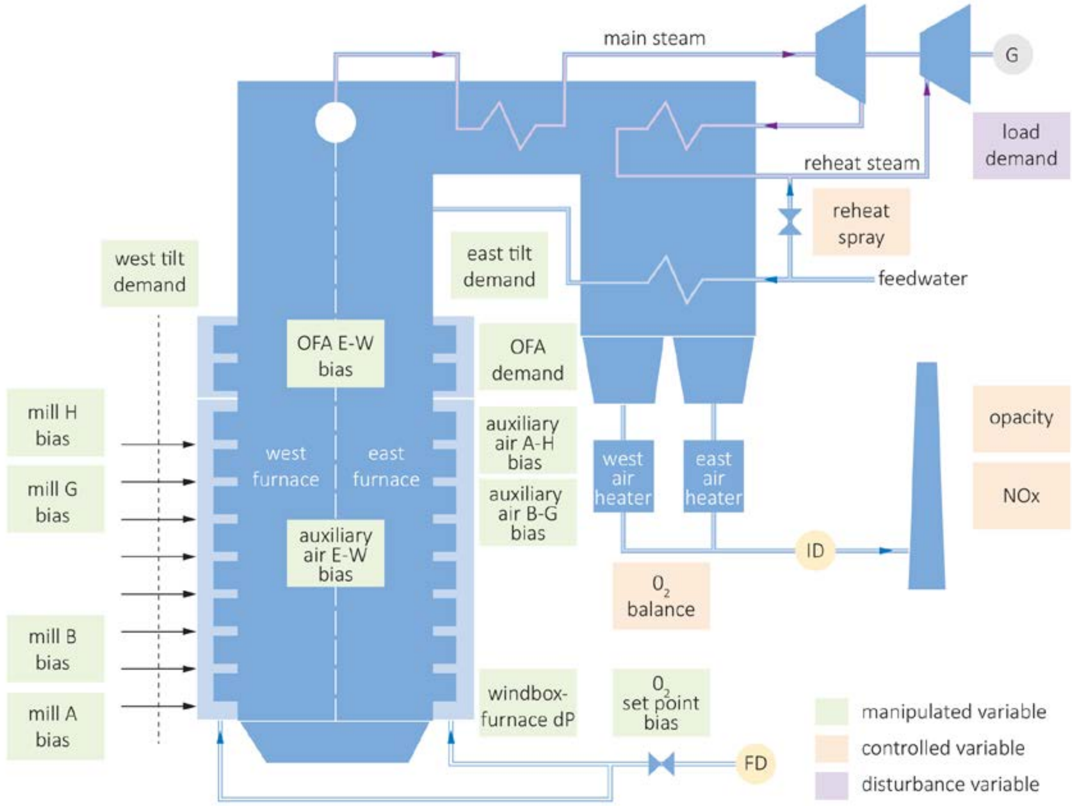

Figure 15 A schematic of a coal boiler indicating key manipulated and controlled variables used by combustion optimisation systems, and the disturbance variable of unit load demand (Immonen and others, 2007)

A range of commercial systems are currently provided by companies which include process control specialists as well as major power industry manufacturers. These products can be designed specifically for combustion optimisation or broadly applicable optimisation algorithms which are employed in several areas of plant control. They may operate as standalone control systems, interface with the plant DCS, or as an integrated software in commercial DCS system (Breeze, 2013b). APC systems are proprietary commercial products involving complex mathematical techniques, and as such, a comprehensive analysis of their individual characteristics is not possible. However, this section will review some of the fundamental approaches employed by a few of the leading APC providers in this field.

4.2.1 NeuCo CombustionOpt

Upon acquiring NOx reduction specialists Pegasus Technologies in 2006, NeuCo became the only company entirely dedicated to optimising power plant operation, and claims to be the market leader in the sector, with over 100 systems currently active (James, 2011; Kirk, 2015). The company has developed four key products on its operating system ProcessLink Platform v3.0, of which CombustionOpt is concerned with combustion optimisation, SootOpt with sootblowing optimisation, and ProcessOpt with overall plant condition and performance. CombustionOpt and SootOpt are frequently installed as the combined package ‘BoilerOpt’.

CombustionOpt uses a combination of APC techniques, including neural networks, direct search, expert rules and model predictive control, to improve unit reliability, efficiency and emissions. As neural networks are static models, CombustionOpt uses them to predict the steady-state result of a variable changes. The complementary MPC component (a later addition to the package), is linear but dynamic, allowing it to predict non-steady-state trajectories of the furnace variables. The MPC is therefore used for rapid control of variables that need to respond quickly to plant conditions such as load changes, steam temperature control, and CO excursions, whilst the neural network focuses on balancing the distribution of air and fuel over the unit (James and Spinney, 2011) (Figure 16). In addition to the neural network and MPC models, NeuCo may use expert rules for tasks such as calculating constraints on manipulated variables or to reactively override the models under special conditions (eg high CO).

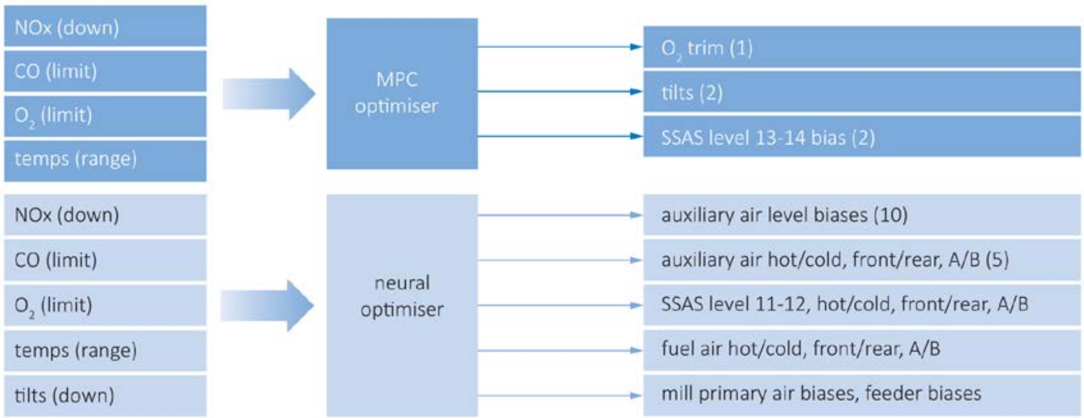

Figure 16 Division of control tasks between the MPC and neural network components of CombustionOpt (SSAS, superheat steam attemperation spray) (James and Spinney, 2011)

Typical performance improvements offered by CombustionOpt include NOx reductions of 10–15%, boiler efficiency increases of 0.5–0.75%, and improved load following, whilst CO levels are controlled to a desired limit (Kirk, 2015). Installation of the software on a 700 MW unit at Belle River Power Plant in Michigan resulted in a 1.63% reduction in heat rate and 20% less NOx, associated with almost halving the excess oxygen used whilst increasing CO within permissible levels (157 ppm). A prime candidate for combustion optimisation, this unit previously operated with excessive levels of excess air as an attempt to mitigate slagging problems by lowering the FEGT, although slagging continued due to imbalanced combustion. Even greater heat rate improvements of up to 2.5% have been achieved over six years of the optimiser being installed on the three 175 MW units at Four Corners Generating Station in New Mexico (Kirk, 2015).

Implementation of CombustionOpt at the 470 MW Gibbons Creek Steam Electric Station in Texas resulted in a 20% reduction in CO emissions, slightly reduced NOx, and significant reductions in use of sprays for superheater and reheater steam temperature control. An improved balance of oxygen across the furnace also allowed the overall excess oxygen to be lowered (deMello and others, 2011).

At some power plants, including Ottumwa, Iowa, and Belle River, BoilerOpt has been implemented in conjunction with the ZoloBOSS system, where the more detailed furnace data provided by the TDLAS grid can be used to aid the optimisation process (Johnson, 2011). This is useful where existing monitoring instrumentation is limited or constraints are particularly demanding and prevailing conditions are highly variable.

Although CombustionOpt installations are currently almost entirely in the USA, a formal partnership agreed between NeuCo and Alstom in December 2014 is likely to lead to more international deployment.

4.2.2 ABB Predict & Control

Manufacturer ABB offer a power plant and combustion optimisation tool under the name Predict & Control which is primarily based on an advanced MPC algorithm. Launched in 2005, the system is designed to be a supervisory layer on top of standard single-loop PID controllers, able to optimise multiple aspects of industrial processes including coal plant (Immonen and others, 2007; ABB, 2006c).

ABB promotes Predict & Control as particularly suited to the treatment of systems with multiple inputs and outputs due to its use of state space models, which are able to capture all aspects of plant process dynamics. This is contrasted with more conventional, linear MPC algorithms which are frequently limited to a collection of single input-single output step response models, and can be challenged by large, unmeasured disturbances to the system. The state space models used in Predict & Control are mathematical representations of a physical system as a set of differential equations which are established using plant test data. The dynamic modelling provided by this MPC system can identify the optimal path between two furnace states in addition to the optimum steady state conditions, allowing it to cope better with process disturbances. A further advantage over simpler optimisation systems is that Predict & Control can be configured using only historical data of closed loop control, rather than needing additional open loop testing.

The state space model also allows the use of another mathematical tool for feedback control known as a Kalman filter, developed for estimating the trajectories of spacecraft. The filter is used to obtain a better estimate of the system's current state, even when faced with noisy and incomplete data (Lundh and Molander, 2002). Each time Predict & Control acts on the system, the controller reads actual process variable values and uses the inputs u and outputs y to estimate the current process state X, input disturbances w and output disturbances h (Figure 17).

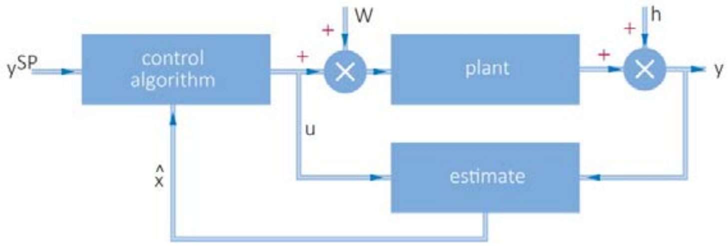

Figure 17 The controller model used by Predict & Control (ABB, 2006c)

This differs from some standard MPC packages that only estimate output disturbances, and enables better estimates of the state and better control of outputs.

Predict & Control has been applied to several aspects of coal plant operation, including combustion optimisation. Installation of the system at the 2094 MW Colstrip plant in Montana in 2008 achieved a 15% reduction in both NOx emissions and excess O_2, in addition to 40% less spray attemperation of reheat steam. Future plans for the model include refinement of the algorithms for additional speed (Spring, 2009).

4.2.3 Emerson SmartProcess

SmartProcess is a process optimisation system produced by Emerson which can be applied to numerous areas of plant control, including combustion optimisation. The system is based on a particular type of fuzzy neural network known as a Takagi-Sugeno-type fuzzy model, in which fuzzy logic is used to better model the transition between closely related states modelled by the neural network (Emerson, 2004; Spring, 2009; Emerson, 2011). SmartProcess has a significant share of the advanced control system market, with over 200 systems installed.

At a 615 MW unit in Newton, Illinois, Smart Process combustion optimisation resulted in a 1% heat rate improvement at high loads and a 20.1% reduction in NOx emissions, with a payback period of nine months (Emerson, 2011).

4.2.4 Invensys Connoisseur

The Connoisseur optimisation system from Invensys also integrates neural networks with MPC to allow an accurate, dynamic response to process changes (Invensys, 2010, 2012). The software offers the ability to optimise over the entire controllable load range, achieving heat rate improvements of up to 1.5% and NOx reduction by 10% to 30% while maintaining high combustion efficiency. Installation of Connoisseur at two 600 MW units at a power plant in Baotou, China, helped lower coal consumption and NOx emissions, and reduce carbon-in-ash levels (Schneider Electric, 2010)

4.2.5 Siemens SPPA-P3000

SPPA-P3000 from Siemens is another product aimed at process optimisation throughout steam power plants, including a combustion optimiser which is based on neural network modelling and sequential quadratic programming. It interfaces directly with the plant DCS, providing existing control loops with bias and set point signals to achieve up to 25% NOx reduction and at least 0.3% improvement in heat rate (Siemens, 2006). Results achieved by this system in combination with ZoloBOSS are described in Section 4.1.6.

4.2.6 EUtech EUcontrol

Eutech Scientific Engineering provide model-based software and sensor technologies for a range of industries, including fossil fuel power generation. Their online combustion optimisation package EUcontrol is noteworthy for using a form of model predictive control based on physical system model rather than a purely data-generated empirical model. A generic CFD model is first adapted to the structure of the target boiler and validated using measured data, before being reduced in complexity to allow for fast, online modelling. The resulting optimiser can operate in an open loop 'advisory' mode or exert direct closed loop control of the plant (EUtech, 2015).

Combustion optimisation with EUcontrol offers efficiency improvements of 0.3% to 1%, a reduction in excess oxygen by –5% to –10%, and –5% to –15% less CO and NOx emissions. Other benefits include reduced slagging, fouling and material stress due to improved control of flue gas temperature. Where necessary, flame temperature is controlled and balanced using data from optical pyrometers such as EUflame. Notable installations of the system include three units at the lignite-fired Niederaussem plant in Germany, comprising the 1000 MW high-efficiency 'BoA' unit and two smaller units. For a 710 MW unit at this plant, excess oxygen was reduced from 4% to 3.2% and boiler efficiency increased from 86.66% to 87.1%. This efficiency gain in turn represented a 7.8% reduction in coal use and a 350,000 euro combined saving in fuel and CO_2 emissions credits (Turoni, 2010).

4.2.7 STEAG Powitec PiT Navigator

Acquired by STEAG in 2012, Powitec has existed as a specialist in automisation systems for combustion processes since 2001, and offers PiT Navigator as automation software for combustion optimisation and steam temperature control. In addition to standard process data, the combustion optimiser relies on flame quality and temperature data from flame imaging (PiT Indicator) and coal quality data from coal mill vibration sensors to build a neural network model. Optimised process set points calculated by this system model are then fed to the power plant control system.

In general, PiT Navigator claims to enable a coal consumption reduction of up to 1%, boiler efficiency increases of up to 0.5%, CO and NOx reduction by up to 30%, and 30% better load dynamics. Applied to two 252 MW boilers at Teifstack Power Plant in Germany, a 0.3% increase in boiler efficiency was achieved, in addition to a 12% reduction in CO, 29 mg/m^3 less NOx, and a 0.5%pt reduction in carbon-in-ash. An even greater efficiency improvement of 0.4% was observed at the 225 MW Fenne Power Plant, also in Germany, along with a 2000 MWh/y saving in auxiliary power consumption (Powitec, NDa).

4.3 Smart sootblowing

The constant build-up of ash deposits on boiler surfaces inhibits efficient heat transfer and can lead to damage of boiler tubing, either through corrosive action or the sheer weight of deposits hanging from pendant superheaters. These deposits are routinely removed by sootblowing, in which high pressure water, air, or steam is blasted through lances at target areas of the boiler. However, excessive sootblowing can itself be damaging due to the erosive action of the water or steam, and should ideally be kept to a minimum (Figure 18). Sootblowing also causes transients in boiler parameters, as exposing heat transfer surface in the furnace leads to lower furnace exit gas temperatures and lower heat transfer in the convective pass, in turn resulting in lower superheat steam temperatures. Whilst ash deposition is gradual, sootblowing induces an abrupt change in local heat transfer, potentially resulting in an unbalanced heat transfer distribution and general loss of performance. Sootblowing can also have a negative effect on emissions, as lower FEGT is associated with raised NOx formation, and the released deposits can increase stack opacity (Blankinship, 2005; Parikh and others, 2014; Hovious, 2011).

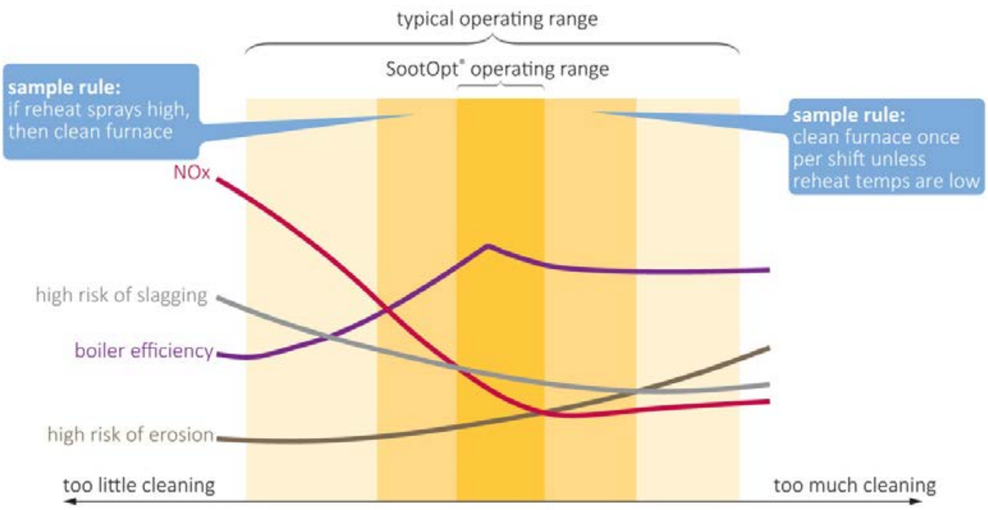

Figure 18 A graphic depiction of how optimised sootblowing can benefit several boiler parameters

Also known as intelligent sootblowing, smart sootblowing systems were introduced to replace conventional sootblower routines which are usually employ fixed interval cycles based on operator experience and recommendations from the boiler manufacturer. Smarter systems actively monitor boiler data such as heat transfer and emissions to determine exactly when and where sootblowing would be best performed. This can have wide reaching benefits on boiler operation including (Sarunac and others, 2004):

- increased boiler efficiency;
- improved furnace heat transfer and lower FEGT;
- reduced NOx emissions;
- improved unit availability;
- reduced furnace slagging and fouling;

- reduced tube erosion and corrosion;
- improved steam temperature control;
- reduced attemperation spray flow rates;
- reduced sootblower usage and maintenance;
- reduced operator workload.

Early forms of intelligent sootblowing were introduced in the 1990s and have since been developed to use increasingly complex protocols. Significant improvements to the process were initially possible by codifying the practices of operators into sets of expert rules, but use of more of advanced techniques including neural networks have more recently been employed to great effect. Sootblowing optimisers draw primarily on heat transfer data from the component boiler sections for their input data, potentially in combination with other furnace parameters such as FEGT and NOx levels.

As a highly effective means of improving boiler availability and efficiency, smart sootblowing systems have been relatively widely deployed, and a large number of optimisation systems are available. Some leading examples are summarised in the following sections.

4.3.1 NeuCo SootOpt

SootOpt from NeuCo is a sootblowing optimisation package based on adaptive neural network models and expert rules, which also forms part of the BoilerOpt product for overall boiler optimisation (Fisher and Spinney, 2012; James, 2011). The optimised system controls individual blowers and coordinates with other control systems without operator input. The boiler is first divided into sootblowing zones according to its layout and the location of sootblowing lances. A set of expert rules to govern when sootblower zones are activated is then identified, based on operator experience and historical data. Each rule has a set of selection criteria associated with achieving a furnace goal, such as raising superheat temperature, as well as an order of priority (Table 4). The highest priority rule which meets its selection criteria at any given time will result in a sootblowing action in zones which it governs.

Table 4 Furnace goals in order of priority for SootOpt at Harrington Unit 3 (James, 2011)

Priority	Goal
1	East and west SH temp down
2	East and west RH temp down
3	SH backpass max time
4	Economiser max time
5	East and west RH temp up
6	East and west SH temp up
7	East and west RH spray down
8	SH spray down
9	Furnace max time
10	SH spray down
11	Reheater pendant max time
12	East and west air preheater gas in temperature down

SootOpt generally results in a marked reduction of sootblowing actions required, with an average of over 600 daily operations reduced to 400 following implementation of the system at Xcel Energy's Harrington Station (Johnson, 2011). A further advantage of the BoilerOpt package is that the combustion and sootblowing optimisation systems can collaborate to achieve shared goals such as reduced NOx and an appropriate FEGT. Installation of the combined software at NRG's Limestone Generating Station in Texas allowed a 15.4% reduction in NOx emissions and an 18.4% drop in CO (Johnson, 2010b).

4.3.2 Taber Knowledge-Based Sootblowing

Specialists in fossil fuel plant optimisation, Taber International implement a 'knowledge-based' sootblowing system based on graphical programming software from Griffin Open Systems (Griffin Open Systems, 2015). The system aims to maintain set point values of boiler temperature and pressure, and is configured with minimum and maximum intervals for blowers to operate at. Every few seconds, an evaluation is performed for each of the blowers against the desired control values. When a sootblowing operation is permitted, the priority of every blower is calculated using a set of tunable, dynamic parameters. For example, reheat section sootblowers may have their ranking factor increased more rapidly than those directed at the economiser as a time constant is approached. The system also responds to changes in fuel, long periods at maximum load, and other disturbance variables.

4.3.3 Siemens SPPA-P3000

A feature of Siemens SPPA-P3000 plant optimisation system, the sootblower optimiser continuously monitors fouling of each heat exchange surface by comparing heat transfer with reference values acquired when clean. These inputs are used as part of an adaptive control protocol which calculates the optimum time for sootblowing of each surface, taking into account plant operating conditions, equipment availability, and operational goals (Siemens, 2006; Parikh and others, 2014). The system then sends individual sootblower activation signals to the existing plant control system in a closed-loop.

Installation of the system at the Hawthorn Generating Station in Kansas City focused on using the optimiser to improve economiser exit gas temperature (EEGT), although additional controls were required for the reheat section to prevent excursion in attemperation spray upon cleaning the heat exchanger. The plant found that EEGT could be effectively reduced, as well gaining improved control of superheat temperature and a heat rate improvement of 1% (Parikh and others, 2014).

4.4 Online monitoring of corrosive species

The increasingly widespread practice of cofiring coal with biomass or recycled fuels can give rise to much more corrosive boiler environments associated with the presence of species such as Cl and alkali metals. This kind of aggressive fireside corrosion can significantly reduce the lifetime of high temperature boiler sections such as superheaters. New tools have therefore been developed for more accurate monitoring of corrosive species in the boiler, as well as the status of the corroding metal components. An improved knowledge of the corrosive impact of specific fuels on the boiler allows the operator to use appropriate proportions of higher risk fuels, rather than being limited by potentially excessive margins of safety. Moreover, the considerable expense of unnecessary shut-downs and boiler maintenance can be greatly reduced.

4.4.1 Metso Corrored

The Corrored system from Metso analyses a portion of hot extracted flue gas for the total sulphur and chlorine concentration (Roppo, 2013). The gas sample is dissolved in water and then analysed by an automated titration at a measurement interval of 10 to 15 minutes. Notably, the system can deal with gas samples up to 1000°C, allowing analysis of flue gas in hot, corrosive regions of the furnace. Data from the Corrored analysis can be used to accurately determine the quantity of Metso's CorroStop fuel additive to add to the furnace for a given fuel blend. This additive, available as a liquid or solid, is an alkali chloride which reacts with SO_2 or SO_3 in the boiler, effectively neutralising their corrosive impact.

Metso are also developing a system for optically monitoring the concentration of KCl in realtime, which will be combined with superheater temperature measurements for an accurate assessment of superheater corrosion risk.

4.4.2 ZoloSALT

Zolo Technologies provide an enhanced version of the laser-based ZoloBOSS furnace monitoring system which includes the capability to measure the alkali metals K and Na in real time (D'Hubert, 2013). Found in high proportions in many biomass fuels, these species lower the melting point of ash and therefore have a strongly enhancing effect on furnace fouling and corrosion. Although ZoloSALT uses the same furnace apparatus as the conventional ZoloBOSS system, detection of the alkali metals is based on their emission peaks rather than the absorption peaks used for O_2, CO and H_2O. This means that concentrations are relative rather than absolute, although they can be calibrated by correlation to the Na concentration in plant coal samples. The measurement is also not able to provide the 2D concentration profiles available for the species covered by ZoloBOSS. Installation of ZoloSALT simply requires additional sensor optics at the control rack which analyses the signal from the furnace detectors.

5 Advanced optical sensors and imaging

Optical sensors convert the physical parameter they measure in to some property of light, such as wavelength, phase, polarisation, or intensity. This optical signal can in turn be converted to an electrical signal but, with communication by optical fibre now ubiquitous, it is also possible to transmit and process the signal in the form of light. Indeed, the use of optical fibre communication offers a number of advantages in power plants, as the signal is unaffected by interference from electromagnetic noise, and fibres can be fabricated from materials which are more resistant to extreme temperatures than electrical wiring. As signals encoded as wavelength are immune from attenuation effects, optical fibre is a much more efficient signal carrier than electrical wires, and the sensitive electrics used to interrogate the signal can be situated well away from the target area (remote sensing). Lastly, in combustion environments optical systems eliminate the ignition risk from sparks present for electrical devices. These advantages have led to advanced optical sensors being identified as particularly suitable candidates for use in future coal-based power systems such as IGCC or AUSC plant, where high temperatures and reducing, corrosive conditions will be even more of a threat. This field is a particular focus of fossil fuel energy research by the US NETL, but applicable technologies are also being developed in R&D programmes for related industries, such as in aerospace and nuclear power (NETL, 2013).

5.1 Optical fibre sensors

Optical fibres are conduits for light, usually comprising a doped silica core surrounded by a silica cladding of higher refractive index which acts to confine light to the core by total internal reflection. Besides their widespread use in signal transmission and processing, optical fibres can themselves be modified to respond to their environment and have inherent sensing functionality for a number of parameters, including temperature, strain, and gas concentrations. Such optical fibre sensors can offer high sensitivity and dynamic range, compact size, and potentially low cost, and a wide variety of devices have been developed and commercialised since the early 1980s (Gupta, 2006; Udd and Spillman, 2011). Although widespread in other industries, the use of optical fibre sensors in combustion applications has been more limited due to the added challenge of operating in high temperature environments. However, significant recent advances in fabrication techniques for materials at the micro- or nanoscale have created new opportunities for developing fibre-based sensors tailored to measuring combustion-relevant parameters at high temperatures. For example, femtosecond lasers can be used to directly micromachine devices into fibres to replace existing devices based on less robust, complex assemblies. Nanoengineering the refractive index of gas-sensitive ceramic coatings can enable their integration with optical fibres as low cost sensors for combustion gases. Finally, the unique attribute of optical fibres to perform distributed sensing at multiple locations along their length could be used as a powerful tool for condition monitoring at high temperatures (NETL, 2013).

5.1.1 Fabry-Perot interferometer sensors

Interferometry uses the superposition of two waves as a means of extracting information encoded in the phase of the original waves. In sensing applications, this usually involves the division of light into a reference beam and a beam whose phase is altered by interaction with the sensing medium. When the beams recombine, a unique interference pattern is produced which depend on the measured parameter. Several types of interferometers can be formed from optical fibres, but the most versatile and widely used for sensing is the Fabry-Perot interferometer (FPI), which simply consists of a reflective cavity acting as a kind of resonant chamber for light (Gupta, 2006; Islam and others, 2014). This cavity can be formed either by two partially reflective mirrors in the fibre itself, known as an intrinsic FPI, or in a piece of another material attached to the fibre or even an air gap, known as extrinsic FPI (Figure 19). The light transmitted or reflected by the cavity shows peaks corresponding to resonances of the space which are extremely sensitive to perturbations affecting the optical path length between the mirrors. For example, as the refractive index of silica has a temperature and strain dependence, intrinsic FPI in optical fibres can act as straightforward sensors for these properties, and have been used as such since the late 1980s (Udd and Spillman, 2011). A huge variety of designs for extrinsic and intrinsic FPI have been demonstrated, but for sensing applications the cavity is usually formed at the end of the fibre, often with the polished fibre end acting as one of the mirrors. The almost point-like nature of such a sensor renders it extremely useful for precise measurements in applications such as medicine (Grattan and Meggitt, 1998).

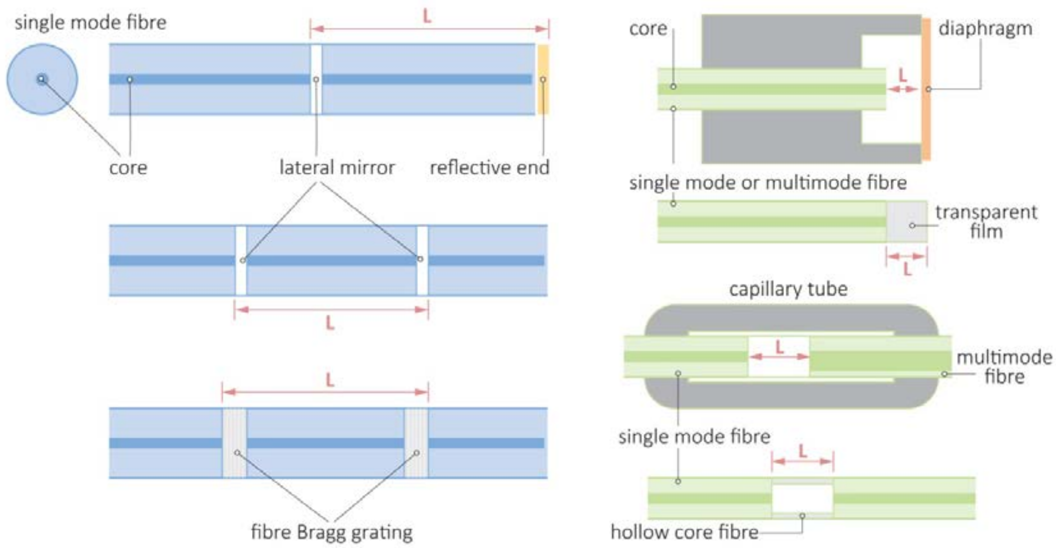

Figure 19 Examples of intrinsic (left) and extrinsic (right) Fabry-Perot cavities

A common technique, particularly for early FPI, is to splice a short length of another material to the end of an optical fibre to act as the cavity. This material can be another length of silica fibre or sapphire, or a thin film. Alternatively, an air cavity can be formed by attaching a length of hollow-core fibre (*see* Section 5.1.3) and capping the end with a silica wafer or diaphragm. The use of a flexible diaphragm in this way enables pressure sensing, as the path length in the air cavity is reduced with displacement of the diaphragm (Pinet, 2009).

In the power plant environment, Fabry-Perot sensors are of particular interest for their use as temperature sensors for temperatures over 300°C. For sensing at lower temperatures, alternative fibre optic devices have achieved commercial success, based on the use of fluorescent dopants at the fibre tip, or a GaAs crystal which has a temperature dependent bandgap (Grattan and Meggitt, 1999; Pinet and others, 2010). At higher temperatures these methods are no longer applicable and strategies for optical fibre sensing become much more limited. Much research has focused on the use of sapphire (Al_2O_3) fibres, whose high melting point (>2000°C) and waveguiding properties make them a useful alternative to silica fibres, in which dopant diffusion becomes problematic at around 800°C (Table 5). A drawback of using sapphire fibres is their poor waveguiding properties relative to silica due to a lack of suitable cladding materials, although $MgAl_2O_4$ is a potential candidate which is stable up to 1200°C. Use of photonic crystal fibres (*see* Section 5.1.3) is another means of avoiding dopant diffusion problems (Ferreira and others, 2013).

Table 5 Examples of high temperature FPI sensor configurations and their performance (SMF, single mode fibre, PCF; photonic crystal fibre; HCF, hollow core fibre; GIF, graded index fibre) (Ferreira and others, 2013)

Configuration	Measurement range (°C)	Sensitivity (change in cavity length/°C)
Etched GIF + SMF	100–700	0.75 pm
PCF FP etalon formed by 157 nm laser	18–800	–
Microotch formed by femtosecond laser	50–1100	0.074 pm
PCF + HCF + SMF	50–1000	–
2 SMF spliced with large lateral offset	200–1000	~41 nm
Air bubble in SMF	100–1000	0.848 pm
SMF + hollow core silica tube	23–1000	8.11 pm
SMF + sapphire fibre	256–1510	–

Efforts to fabricate sapphire-based FPI have mostly focused on the assembly of extrinsic FPI with an air cavity to act as the resonant cavity. Research at Virginia Polytechnic have developed such a device following the format depicted in the top right of Figure 19, in which a sapphire wafer is held a short distance from the tip of a sapphire fibre by a supporting alumina tube structure (Ivanov, 2011; Wang and others, 2012). In 2007, this sensor was tested in a real gasifier environment and found to operate successfully under temperatures of 1100°C to 1500°C for seven months, during which time thermocouples had to be replaced twice. A major challenge in assembling this kind of multi-component FPI is fusing pieces together in such a way that will withstand high temperatures, as well as developing a straightforward and reproducible procedure with constant cavity length. Whilst early techniques employed epoxy resin, fusion by heating the joint with a laser or electric arc is now more common (Wei and others, 2008).

Research at Clemson University has instead adopted the novel approach of using high intensity femtosecond laser pulses, which can ablate most solid materials in a precise fashion, to 'micromachine' air cavities in single crystal sapphire fibres (Xiao, 2014). These extrinsic FPI can take the form of a square hole or rectangular notch at the fibre tip, and avoid problems of weak bonds or mismatched coefficients of thermal expansion present in assembled devices. The sensors were demonstrated up to 1600°C, and can take simultaneous pressure and temperature measurements. A similar device has been made commercially available by Oxsensis for use in gas turbines and other applications, providing integrated sensing of static and dynamic pressure and temperature at up to 1000°C and 60 bar (Figure 20). A micromachined sapphire tip is connected to a silica fibre via an alumina tube, along which there is a sufficient thermal gradient for the silica to be kept below its upper temperature limit, and the whole assembly is packaged in Inconel. Whilst the vacuum cavity in the tip acts as a pressure-sensing FPI, the solid sapphire region defines a FPI cavity for temperature sensing which is also used to correct for the thermal expansion of the vacuum cavity (Oxsensis, ND; Hemsley, 2015). As part of the collaborative EU-funded 'HEATTOP' research project, these sensors have been successfully trialled by Siemens for dynamic pressure sensing in gas turbine test rigs, and Oxsensis are currently aiming to develop all-sapphire devices for monitoring turbine gas temperatures at over 1000°C.

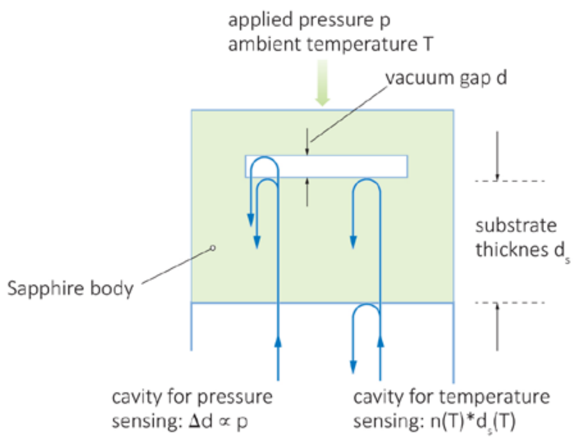

Figure 20 An optical fibre capped with a micromachined sapphire tip acts as a high-temperature Fabry-Pérot interferometer sensor for temperature and pressure (Oxsensis, ND)

5.1.2 Fibre Bragg grating sensors

Bragg gratings are periodic modulations in the refractive index of a fibre which cause the reflection of specific wavelengths of light (Figure 21). They can be 'written' into optical fibres doped with germanium using UV lasers which induce a permanent change in the refractive index at precise points. Fibre Bragg gratings (FBG) are widespread in optical fibre communication technologies and they are also highly applicable to sensing applications, not least because the wavelength reflected by the grating is highly sensitive to both temperature and strain. By extension of this, it is also possible to introduce chemical sensitivity with fibre coatings which have a strain response to adsorbed species. A key advantage of Bragg gratings is that a large number can be written into the same fibre and used to take simultaneous measurements at different locations – known as multiplexing or distributed sensing. However, there is a trade-off between the number of gratings and the dynamic range of the measurements achievable at each grating.

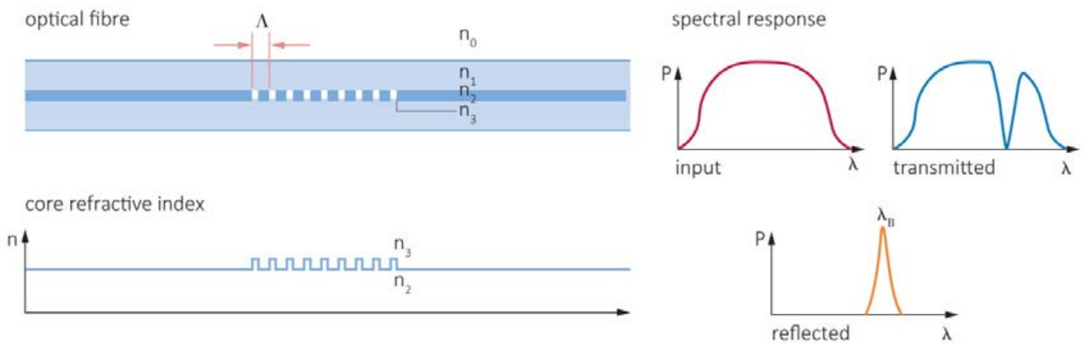

Figure 21 Fibre Bragg gratings (n, refractive indices; λ, wavelength; P, power)

Commercially, FBG strain sensors are widely used in condition monitoring of large structures such as bridges and buildings, where gradual displacements can be measured over long periods of time. However, FBG fabricated in the conventional fashion in Ge-doped fibres are not suitable for applications in high temperature environments as the refractive index variation is annealed out over 450°C (Mihailov, 2012). Alternative methods have therefore been developed to create gratings capable of withstanding higher temperatures. Application of high intensity UV pulses, which essentially damage the silica by ionisation, can produce so-called Type II gratings which are stable up to 1000°C, although they suffer from reduced mechanical strength. High temperature FBG can also be written with femtosecond pulses of an infra-red laser, which has the added advantage of being applicable to any fibre material, including single crystal sapphire. Research at the Institute of Photonic Technology in Germany has used this method to fabricate sapphire FBG temperature sensors stable up to 1745°C, potentially offering a useful alternative to FPI sensors in sapphire with the additional feature of multiplexed sensing along the fibre length (Busch and others, 2009). These high temperature FBG sensors could be particularly well-suited to monitoring the interior of gas turbines, where accurate measurement of the hot gas working temperature is a critical control parameter. One of the drawbacks of sapphire fibres for FBG, however, is that the lack of cladding leads to highly multimode transmission properties which lower the sensitivity of their response to temperature and strain. This research circumvented this problem by using an optical technique to excite only the fundamental mode of the sapphire fibre.

Another method of raising the temperature resistance of an FBG, known as chemical regeneration, permeates the fibre with hydrogen gas prior to a conventional UV writing process, resulting in the formation of hydroxide groups and a stronger refractive index variation. The fibre is then annealed at 600–700°C, eliminating the original grating, before a much higher temperature ‘regeneration’ step which generates a new longer wavelength grating. Although the mechanism behind this process is not entirely clear, the new grating is stable to over 1000°C and can be cycled repeatedly (Zhang and Kahrizi, 2007). The later discovery that H_2 gas need only be present prior to the annealing stage has led this process to be successfully used to bestow high temperature resistance on low cost commercial FBG (Lindner and others, 2011; Chen, 2013, 2014). This research has gone beyond temperature and strain sensing to produce a multiplexable flow sensor capable of operating at 850°C. In addition, the gratings can be used in ‘distributed Bragg reflector’ (DBR) laser diodes which are used to generate lasers for a range of sensing applications such as measurement of vibration and turbulence.

The strain response of FBGs extends to the detection of dynamic strain in the form of acoustic vibrations. This capability has been exploited by research at the University of Massachusetts which aims to map temperature profiles over a whole coal furnace using multiplexed FBGs to perform acoustic pyrometry. Fibres would be wrapped around the furnace at various levels, each containing several FBG detectors, whilst the sound waves themselves would be optically generated by stimulating coatings of photoacoustic material on the fibres (Zhou and others, 2015).

5.1.3 Gas sensors using microstructured fibres

Although the light travelling through the core of an optical fibre is totally internally reflected at the boundary with the cladding, the electromagnetic field decays into the cladding and beyond. This ‘evanescent field’ is extremely useful for sensing applications as it provides a means with which the light within the fibre can interact with the exterior environment, particularly with gaseous species. Optical fibre sensors based on this principle usually have their structure altered in some way so as to bring surrounding gases into close proximity with the core (Phoenix Photonics, 2014). A common means of achieving this is simply by polishing away one side of the cladding to form a D-shaped fibre (Figure 22) with one flat surface where the evanescent field from the core is still strong (Chandani, 2007).

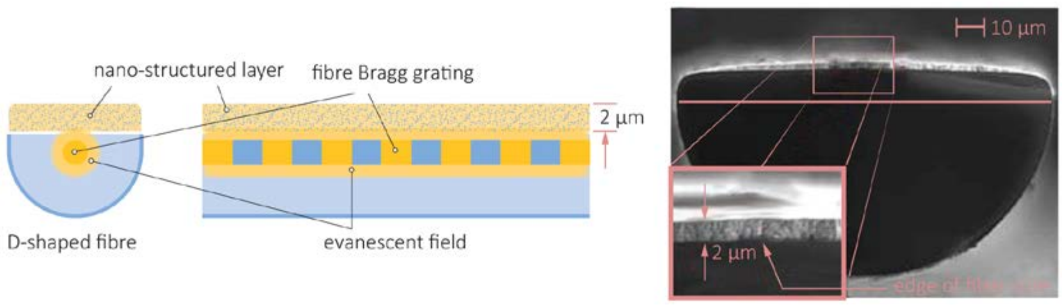

Figure 22 A D-shaped fibre modified with a gas-sensitive ceramic film (Chen, 2014)

There are several ways in which the presence of gas molecules in the evanescent field of the fibre can be detected. Perhaps the most straightforward is by absorption spectroscopy, as the characteristic gas absorptions will appear as losses in light transmitted through the portion of fibre exposed to the gas. However, it is also possible to coat the flat side of a D-shaped fibre with a functional material which has a structural or optical response to the target gas. In particular, a change in refractive index induced by gas adsorption can be detected by a fibre Bragg grating in the functionalised region, as a change in the reflected Bragg wavelength will be observed. For this purpose, Bragg gratings with a long period of refractive index variation are particularly well-suited, as they promote strong coupling between the core modes of the fibre and the evanescent field (Quero and others, 2011; Zhou and others, 2005).

This approach has been adopted by ongoing research at the University of Pittsburgh, aimed at the detection of ammonia gas: an important control parameter in operation of selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR) (Chen, 2014). Tin oxide was selected as a functional coating due to its widespread use in electronic gas sensors, where it shows a high selectivity and sensitivity to adsorption of reducing gases (Figure 22). First, the refractive index of SnO_2 had to be engineered to be compatible with light-guiding in the fibre, achieved by crystallising a nanoporous film of the material around a removable polymer scaffold. Although the adsorption of ammonia to the oxide film could be readily detected in absorption spectroscopy of the fibre, the refractive index change and impact on the Bragg wavelength was not observed. The research plans to explore other coatings such as TiO_2, as well as other means of engineering the refractive index. Other groups have explored the use of a similar technique for sensors aimed at detection of syngas constituents H_2 and H_2S, with a focus on identifying new nanocrystalline ceramics sensitive to these gases (NETL, 2012).

Another means of allowing gas molecules to penetrate close to the fibre core is to use a porous cladding material, with smaller pores particularly effective due to less gas being needed to fill the space. One means of synthesising a microporous glass cladding is to use two glasses which separate into two highly interconnected phases, before dissolving one of the materials to leave a porous network. This is the approach adopted by research at Virginia Polytechnic Institute, which also achieved a roughly radial alignment of the pores around the fibre core, further easing the passage of gas molecules towards the core (Pickrell and others, 2014). This pore alignment should provide a significant advantage over conventional porous silica which is severely limited by slow gas diffusion (Pacholski, 2013). The sensing fibres are probed in the mid-IR spectrum (3–15 μm) which corresponds to absorption peaks for relevant gases such as CO_2, CO, N_2O, and SO_3, as well as being in a transmission window.

Holey fibres and photonic crystals

Photonic crystals are a unique class of microstructured optical fibres in which longitudinal air holes are arranged so as to alter the refractive index of the fibre in a prescribed manner. The periodic variation in refractive index provided by these holes can have a confinement effect on light in a manner that can be seen as analogous to the effect of ionic crystals on electrons. Photonic crystal structures can be used to give the cladding a suitable refractive index for light confinement in the core without having to use dopants in the silica. This is useful for high temperature operations at which dopant diffusion can start to occur. Alternatively, the microstructured cladding can even be used to confine light in a core which is itself a hollow tube (Figure 23), and thus particularly interesting for gas sensing applications (Hoo and others, 2003).

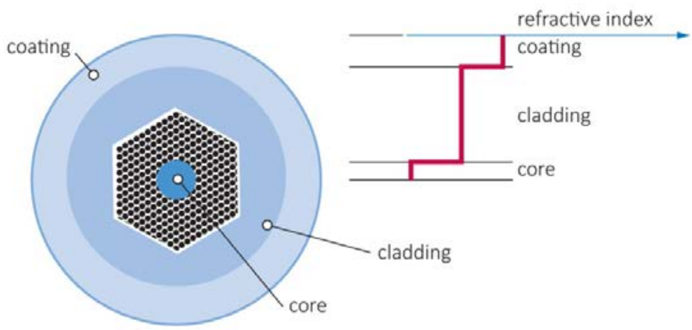

Figure 23 Photonic crystal structure with a hollow core (NKT Photonics, 2014)

A photonic crystal structure employed by Wang and others for high temperature gas sensing uses a sapphire fibre core surrounded by a hexagonal arrangement of six more sapphire fibres (Pickrell and others, 2014). In the sensing region, a section of the central fibre is removed to leave a hollow core which essentially acts as a microscale sample cell for absorption spectroscopy.

5.1.4 Distributed optical fibre sensing

A particularly powerful feature of optical fibres as sensors is that they can be used for sensing a parameter along their entire length, known as distributed sensing. Several techniques exist for interrogating a fibre in this way, all essentially based on probing the fibre with light and detecting various forms of backscattered signals. The arrival time of the returning signals can be correlated to location in the fibre and thus used to characterise properties of the fibre along its length (Bao and Chen, 2012). The signal from elastic Rayleigh scattering of light from fibre inhomogeneities is temperature and strain invariant, so more difficult to use in sensing applications, although widely used for detecting transmission losses in the fibre. Raman scattering on the other hand, involves the interaction of the light pulse with material vibrations (phonons) and is therefore highly temperature dependent. Numerous distributed optical fibre temperature sensors based on detection of the Raman scattered signal are commercially available, attaining temperature accuracies of 0.5 K, 1 m spatial resolution, and ranges of tens of kilometres. In process plant, these devices are aimed at detecting hot spots in long structures such as conveyor belts, or maintaining cryogenic temperature in gas storage. Although the majority cover a fairly limited temperature range, the DTSX3000 from Yokogawa has a range from -220°C to 800°C, with 0.02°C temperature resolution over 10 km (Yokogawa, 2014; AP Sensing, 2009).

Most commercial distributed sensing using Raman or Rayleigh scattering employs a technique known as optical time domain reflectometry (OTDR), in which a light pulse is used to probe the fibre and the scattered signal is measured as a function of time (Figure 24). Optical frequency domain reflectometry (OFDR) is an alternative where a tunable laser source interrogates the fibre over a range of frequencies, and can attain increased spatial resolution. A sensor based on Raman scattering OFDR is currently used in distributed temperature sensing by LIOS technologies, but is not in widespread commercial use (LIOS, 2014). However, with the appropriate set up, OFDR can also be used to obtain temperature and strain information from the Rayleigh scattered signal, opening up new distributed sensing possibilities.

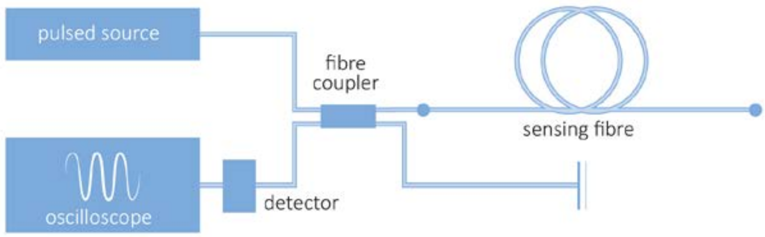

Figure 24 A schematic of an OTDR arrangement

Whilst Raman scattering involves optical phonons, interaction between the light pulse and acoustic phonons (sound waves) is known as Brillouin scattering, and is potentially even more useful for distributed sensing. Most significantly, Brillouin scattering is sensitive to strain as well as temperature, as both parameters cause silica density variations which affect the speed of sound. Secondly, the frequency shift between the probe and scattered wave (Brillouin shift) is much smaller than in Raman scattering, so both signals can be transmitted with high efficiency (Galindez and Lopez, 2012).

A much stronger Brillouin scattering signal can be obtained by actively generating acoustic waves in the optical fibre. Known as stimulated Brillouin scattering, this process uses a laser pulse at a particular frequency to set up a travelling acoustic wave in the fibre through an interaction known as electrostriction. This wave can be thought of as a travelling FBG, or periodic variation in refractive index, and therefore enhances the sensing signal. A short pulse probe is then used to obtain a distributed profile of Brillouin shift along the fibre length (Yu and Wang, 2014; Alahbabi and others, 2004). A few commercial systems, such as DITEST from Omnisens, are based on stimulated Brillouin scattering, with faster measurement times as the principal benefit offered over Raman-based devices.

Research at Virginia Polytechnic has looked at developing sensors based on stimulated Brillouin scattering for detecting hot spots in the refractory lining of coal gasifiers (Yu and Wang, 2014). The high temperature, reducing environment in gasifiers subjects the refractory to very rapid corrosion, and prediction of the remaining refractory life is challenging. The current strategy, relying on scheduled shut-downs of the gasifier for inspection and refractory replacement, is conservatively frequent and very costly. There is therefore a strong incentive to develop an online temperature sensor which can detect early on when 'hot spots' arise in the refractory, indicating the start of material failure. The distributed optical fibre sensor would be wrapped around the gasifier between refractory layers.

Initial tests on the optical fibre sensor achieved a spatial resolution of 1 m and a temperature resolution of 5°C at 1000°C (Figure 25). Tests simulating the gasifier environment were then conducted using a bench-scale furnace and Inconel packaging for the optical fibre, achieving hot spot detection at 1 m spatial resolution over a total span of 600 m.

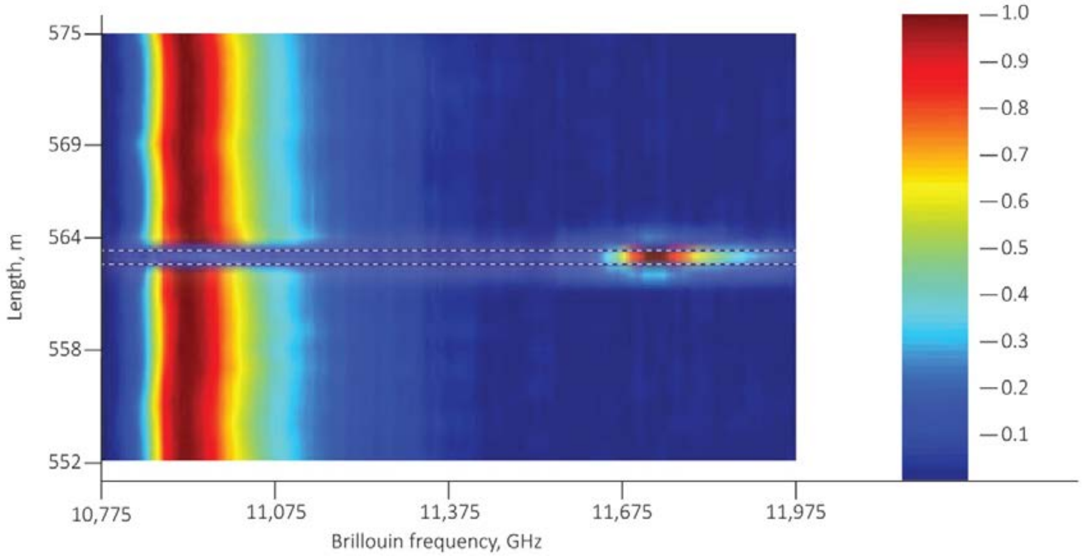

Figure 25 Frequency shift of the reflected light corresponds to temperatures along the fibre, making it possible to detect a short heated section (Yu and Wang, 2014)

It may also be possible to extend the distributed sensing principle beyond temperature and strain to encompass pressure and gas sensing as well. Research at the University of Pittsburgh has applied a Rayleigh scattering OFDR technique to fibres microstructured with longitudinal air holes to achieve distributed pressure sensing. Using a principle employed in other optical fibre hydrogen sensors, it was found that coating a fibre with palladium also enabled distributed hydrogen sensing, due to the expansion of the palladium lattice upon the adsorption of hydrogen. A spatial resolution of 1 cm was achieved for both techniques and, although demonstrated at 800°C, the sensors should be viable to temperatures over 1000°C.

5.1.5 Embedded optical fibre sensors

There is increasing interest in the potential for embedding optical fibre sensors within power plant components such as steam pipes and turbine blades through the use of additive manufacturing techniques. In addition to eliminating the need for protective packaging and device installation, greatly improving sensor survivability, placing the sensor within the component itself provides insight on internal material properties which are particularly useful for condition monitoring. Indeed, embedded fibre optic sensors are already widely used for structural health monitoring in civil engineering, where they can be relatively easily incorporated with materials such as polymer composites and concrete. Application of this principle to the metal and ceramic components used in power plants, however, must make use of the emerging technology known as additive manufacturing. This term encompasses a range of techniques which can be used to build solid objects layer by layer based on data from a computer assisted design programme.

Research at the University of Missouri is investigating the application of additive manufacturing for embedding multiplexed strain sensors on silica and sapphire optical fibres (Dunst and others, 2015). A technique known as freeze form extrusion is used for additive manufacturing of refractory material, in which a water-based ceramic paste is deposited in layers and solidified by freezing, whilst steel parts are formed by laying down successive layers of foil which are welded together or cut into the desired shape with lasers. The optical fibre sensor can then be placed within the component at the appropriate stage, before manufacturing is completed. However, forming a good interface between the two materials can be problematic, and mismatched coefficients of thermal expansion can lead to delamination and fibre breakage. Complementary work at the University of Cincinnati has therefore investigated the use of silicalite as an interfacial, adhesive material. VirginiaTech work is developing FBG sensors which use acoustic signals to monitor temperature, strain, corrosion, and material defects.

The EU-funded research project 'OXIGEN', concerned with the additive manufacturing of turbine blades from specialist alloys, has also incorporated the embedding of optical fibre sensors with work performed at Herriott-Watt University in the UK (Mathew and others, 2014; European Commission, 2013). This work is based on selective laser melting, an additive technique which uses dual laser beams to selectively fuse together a metal powder, and employs fused silica capillaries to encapsulate and protect the fibre sensors.

Optical fibre devices based on FBG or FPI have been identified as highly suitable candidates for embedded sensors. A novel concept studied at Virginia Polytechnic is the use of FBG sensors embedded in combination with photoacoustic fibres, which are able to generate sound waves from light. The acoustic signals detected by the FBG can then be used to derive information on the temperature, strain, corrosion, and defects in the host material (Hu and others, 2015).

5.2 Advanced spectroscopic techniques

In the last decade, detailed spectroscopic analysis has increasingly replaced single wavelength photometric techniques for flue gas analysis in power plants, particularly for the purposes of emissions monitoring at the stack. Usually in the form of Fourier transform infrared spectroscopy, such methods require flue gas extraction and extensive sample conditioning but provide levels of a much wider range of species than previously available (Hodgkinson and Tatam, 2013). More recently, absorption spectroscopy using tunable diode lasers has become a useful tool for highly sensitive in situ measurement of gas concentrations and temperature. However, there remains a wide range of spectroscopic techniques which could usefully be applied to coal plant sensors if made economically viable. Newer techniques using laser irradiation in the near-IR region, rather than broadband sources are also highly suitable for coupling with optical fibres, allowing remote monitoring of the process.

5.2.1 TDLAS for gasifiers

Absorption spectroscopy using tunable diode lasers has become an established technology for gas and temperature monitoring in high temperature regions of coal furnaces (*see* Section 4.1.6). However, application of the technology to gasifiers presents a greater challenge, due to the high pressures, temperatures, and high concentrations of particulate present. High pressures have the effect of broadening and blending spectral peaks, absorbance is reduced at high temperature, and particulates cause scattering and significant transmission losses in the laser beam.

Research at Stanford University has nevertheless aimed to adapt TDLAS to the gasifier environment as a means for monitoring the key control variables of CO and CH_4 concentrations, as well as water and CO_2 (Hanson and others, 2014). To enhance the sensitivity of the technique, wavelength modulation spectroscopy is employed, in which the laser signal is modulated at a particular frequency which can then be used to separate the detected signal of interest from noise and scattered light. In order to apply this technique to all the measured species, a dedicated laser is used for each of the gas species monitored, resulting in four separate lasers which are combined via time multiplexing, essentially meaning that each laser takes a measurement in turn.

The system has been successfully applied to the NCCC demonstration gasifier in Wilsonville, Alabama, monitoring at a location 30 m downstream of the particulate detection device which follows the gasifier. Even here, transmission losses of 99.9% are encountered due to the high pressure and particulate levels. Nevertheless, the system compared very favourably with the conventional extractive gas analysis technique based on gas chromatography, showing a much quicker response to transients and generally superior time resolution (Figure 26). A sensitivity limit of 200 ppm was achieved for CO and 300 ppm for CH_4.

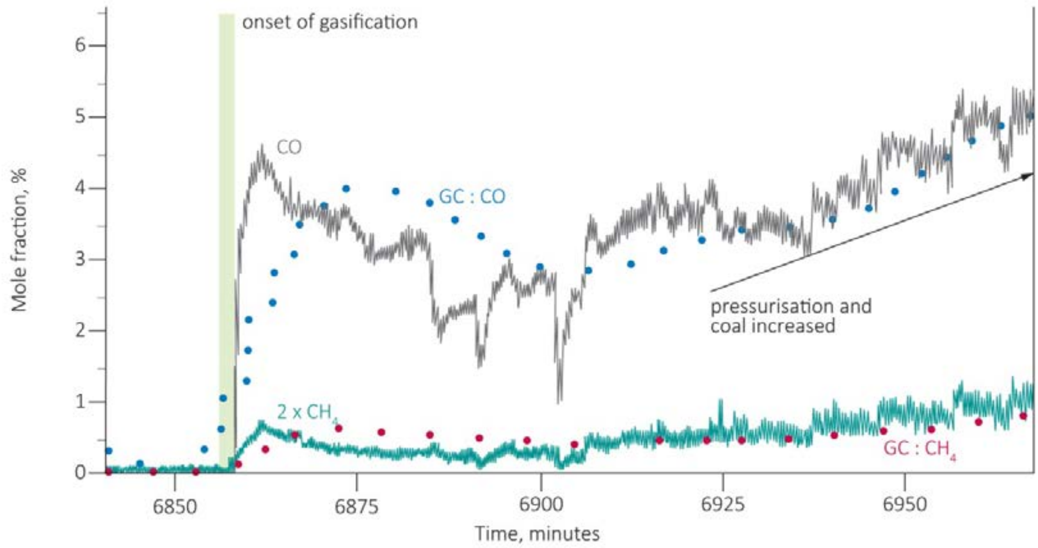

Figure 26 Improved detection of the onset of gasification using TDLAS compared to gas chromatography (GC) (Hanson and others, 2014)

Cavity ringdown spectroscopy (CRDS) is a form of absorption spectroscopy in which the signal is enhanced by using a reflective cavity as the absorption cell. When a laser is in resonance with a cavity mode, light is reflected thousands of times between the reflective walls, giving a much larger absorption path length. The concentrations of absorbing species in the cavity are detected by the time it takes light intensity in the cavity to decay following removal of the probe laser – known as the ringdown time. As this technique is highly sensitive to trace gas concentrations, it has been the subject of much interest for continuous emissions monitoring of trace regulated species in flue gas. Although investigated early on as a means of monitoring mercury (Carter, 2004), other techniques have superceded it for commercial application. On the other hand, with recently implemented limits on HCl emissions from fossil fuel plant are approaching the detection limits of current instruments, and research at Sandia National Laboratory has focused on the use of cavity ringdown spectroscopy for this species. A recently developed commercial apparatus for the detection of trace HCl by CRDS has been developed by Tiger Optics in collaboration with EPRI, achieving a lower detection limit of 1 ppb (Tiger Optics, 2014; Leggett, 2014).

In addition to applications in continuous emissions monitoring, CRDS has been applied to the detection of trace soot species in coal flames such as acetylene, which is a precursor of soot formation and therefore and indicator of poor combustion (Humphries and others, 2014).

5.2.2 Raman spectroscopy

Raman spectroscopy is based on the scattering of light rather than absorption, and is widely used for the study of certain species which do not show absorption peaks in IR spectroscopy such as the diatomic elements N_2, H_2, and O_2. However, it has so far seen limited use in industrial gas analysis applications due to its low signal strength unless very high laser powers are used. The weak effect of water on Raman spectra, as well as a high dynamic range and small sample size, give the technique considerable potential for applications such as syngas analysis and monitoring of recirculated flue gas. Research effort has therefore been directed towards achieving a low-cost and enhanced signal strength Raman technique for industry. Although a range of techniques for enhancing the Raman signal have been developed, industrial research has identified largely the use of reflective Fabry-Perot-type cavities as sample cells as the lowest cost solution. The amplification of the laser signal in these cavities permits the use of commercial low powered lasers and standard CCD array spectrometers (NETL, 2012; Alman and others, 2014; Thorstensen and others, 2014). A principal achievement of these systems is the ability to take very rapid measurements (less than one second), at detection limits of up to 0.5%.

5.3 Flame imaging

Monitoring of pulverised coal flames with CCTV cameras is frequently employed by coal plant as a means of visually ensuring a stable flame is present. However, as the use of more challenging and variable fuels such as low rank coals, coal blends, and biomass becomes more common, there is a growing need for more advanced imaging technologies and image processing software which can quantify flame stability and help to optimise combustion. Whilst video camera images represent a vast quantity of useful data for the plant, extracting useful, quantitative information can be challenging.

The PiT Indicator system from STEAG Powitec is a commercial system which deploys a CCD camera at each burner to provide a combustion optimisation system with real time variation in quantified parameters such as flame shape, ignition point, and burnout characteristics (Powitec, NDb). The thermographic RGB images generated by the camera are analysed through a series of well-defined polygon and line sections and the data are plotted with respect to time. An installation of this system at Tiefstack Power Plant in Germany replaced the CCD cameras with higher speed CMOS cameras (Funkquist, 2011).

Research at the University of Kent has developed a flame monitoring system which integrates digital CMOS camera images with spectral data from photodetectors for online characterisation of flame properties (Lu and others, 2005, Sun and others, 2011). A water-cooled optical probe receives light from the flame which is then split between the camera and photodetectors for emission intensity at key UV, visible, and IR frequencies (Figure 27). The photodetector signals are used to obtain the characteristic oscillation frequency of flame emissions also known as flicker. Statistical analysis of the flame images can yield a range of useful geometric and luminous parameters such as ignition point, spreading angle, and brightness in addition to the temperature distribution of the flame. Temperature at each pixel of the image is calculated using two-colour pyrometry based on the red and green channels of the camera.

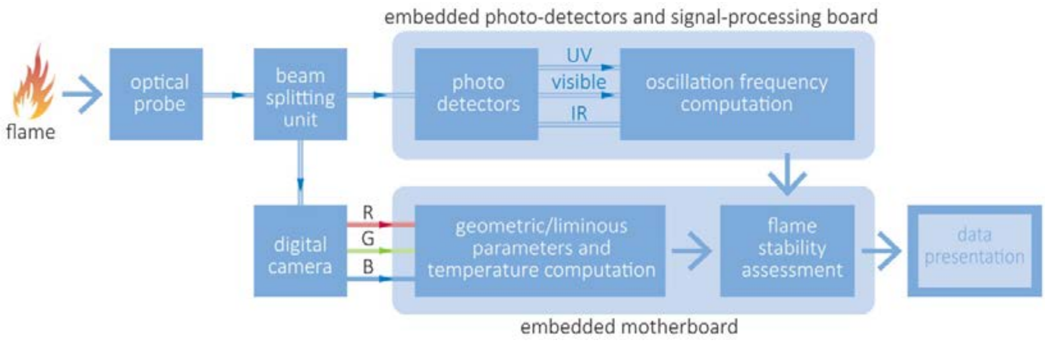

Figure 27 A flame monitoring system combining both digital imaging and single point spectral measurements (Sun and others, 2011)

Other research has made use of a statistical tool known as a hidden Markov model, usually employed for text and speech recognition, to extract useful information from the large amount of data in flame images (Chen and Hsu, 2010). With this model, it is possible to quantify the evolution of the flame over time as well as its spatial distribution, taking into account gradual variation of flame properties, and allowing early detection of an abnormal flame.

NETL-funded research has focused on developing flame imaging systems for gasifiers, where the change in flame quality over time could provide a useful indicator of the condition of fuel injectors, and help predict when they will need replacing (NETL, 2012). Work by the GTI and North Carolina State University has developed a prototype system based on a fibre optic bundle camera, which has been tested on Canmet's gasifier pilot prior to demonstration in a commercial gasifier at Wabash River. The project demonstrated that the sensor technology can identify coal combustion steps such as devolatilisation, char heating and burning, and is therefore also useful for obtaining close control of the gasification process and adjustment of air/fuel and water/fuel ratios.

6 High temperature microsensors

The rapid miniaturisation of electronics, so apparent in the field of computing, is also allowing the development of miniaturised sensors which offer several advantages to sensing in the power plant environment. Mostly based on thin film deposition techniques which result in component thicknesses on the microscale, such devices can be collectively termed microsensors, although a broad range of transduction mechanisms are employed. Sensors on this scale can be placed in previously inaccessible locations such as the interior of gas turbines, or deployed in large arrays which can feedback a detailed picture of plant condition or process variables. Furthermore, their relatively compact and simple structures allow for robust device packages which can operate at unprecedented high temperatures of over 600°C, suitable for direct monitoring of the furnace, gasifier, or turbine environment. The abundance of mass production techniques developed for microfabrication of electronics mean that microsensors also have the potential to be low-cost alternatives to conventional sensors. However, for high-temperature devices, these techniques need to be applied to more novel materials which exhibit high stabilities (NETL, 2013).

6.1 High temperature gas sensors

Online monitoring of several gas species is integral to emissions control and optimisation of combustion and gasification processes. Commonly used methods relying on gas extraction suffer from a delayed response and consequently inaccurate measurements, so there is a strong incentive to develop in situ sensors. However, whilst numerous gas sensing technologies are available for low temperature applications, options are much more limited at temperatures over 300°C, at which material stability and poor selectivity can become serious issues. Currently, sensors for oxygen and NOx are the only examples to see widespread commercial use in the combustion environment, and research into high temperature gas sensors has concentrated on both improving these devices and developing sensors for combustion and gasification products including CO, CH_4, and H_2. Several sensing mechanisms can be employed for electronics-based gas sensing, but many are fundamentally based on the redox behaviour of gases and, particularly at high temperatures, lack the degree of selectivity inherent to spectroscopic-methods. Reducing 'cross-sensitivity', or the unwanted response to other gases, therefore remains the principal challenge for these kinds of gas sensors. Selection of appropriate materials is key for most devices, drawing largely from a select group of gas-sensitive metal oxides which are stable to high temperatures, in addition to the highly stable 'perovskite' oxides, and composites of combinations of these. Pure metals such as platinum and gold also play a role as catalytic or inert electrode materials (Moos and others, 2009; Liu and others, 2014b; Richter and Fritze, 2014). Materials screening programmes are therefore an important tool, in addition to the use of microstructuring techniques which can produce the large surface areas required for gas-surface reactions.

Another useful technique for reducing cross-sensitivity is the use of arrays of several sensor types of varying selectivity for each species. The concentration of each gas species is then obtained from a characteristic combination of signals from each sensor, rather than a single response (Richter and others, 2009).

6.1.1 Solid electrolyte-based sensors

Equilibrium potentiometric sensors

A solid state electrochemical cell can be used to determine a gas concentration based on the measurement of its chemical potential relative to a reference concentration. In its simplest form, the cell consists of two compartments separated by a solid ion-conducting electrolyte with a porous coating of catalytic electrode material (typically Pt) on either side. The sensor can be operated either in potentiometric mode, where the cell voltage is measured, or amperometric, in which a voltage is applied and the resulting current measured as ions are actively pumped across the electrolyte. The former approach is particularly useful for sensing highly dilute species, due to its increased sensitivity and logarithmic dependence at lower concentrations, and the power of the technique is demonstrated by the widespread use of the zirconia-based potentiometric oxygen sensor (*see* Section 4.1.1).

However, electrochemical sensors like the oxygen sensor, which use air as a reference are difficult to miniaturise and poorly-suited to placement in inaccessible locations removed from the furnace or gasifier exterior (Liu and others, 2014b). A key development in commercial oxygen sensors has therefore been the replacement of the air reference with solid references based on a metal-metal oxides junction such as Ni/NiO, which provides a constant equilibrium oxygen partial pressure and is still effective at high temperatures (Hu and others, 2012). Such metal/metal-oxide based sensors also need to be tightly sealed to prevent oxygen penetration into the solid reference electrode, which is challenging and strongly affects the long-term stability of the sensors at high temperatures. To completely avoid sealing issues, all-solid-state reference electrodes have been developed which bypass the generation of oxygen and use an oxide only. For example, solid ceria/ZrO2, which stores oxygen at high temperatures, is an effective reference, despite the drawback of a narrower voltage range (Rajabeggi and others, 2004).

Amperometric NOx sensors

A further limitation of potentiometric sensors of this type is the need for electrolyte materials which conduct ions corresponding to the species of interest. At present, the oxygen-conducting yttria-stabilised zirconia (YSZ) is the only suitable material which is also viable at high temperatures. A number of more elaborate cell designs have therefore been pursued in developing YSZ-based electrochemical sensors for other species such as NOx and SO_2, usually employing novel electrode materials with sensitivities to specific gases. Whilst the redox activity of NO, for example, will also contribute to the zirconia cell potential by reacting with oxygen ions, its much lower concentration means that their contribution to the equilibrium voltage is negligible.

Commercial NOx sensors have therefore made use of zirconia cells operated in amperometric mode, where the addition of a porous barrier limits gas diffusion and makes the current limiting (DeBarber and Mizutani, 2011; NGK, 2014). For example, a design from Horiba employs a series of sample chambers and standard zirconia cells operated in amperometric mode (Figure 28). In a first chamber, a zirconia cell pumps oxygen out of the flue gas sample whilst measuring the oxygen concentration, before the depleted air passes through a membrane into a second chamber. Here, a second cell pumps remaining oxygen from the chamber, whilst an associated cell with a NO selective electrode material (Rh) measures a NO signal.

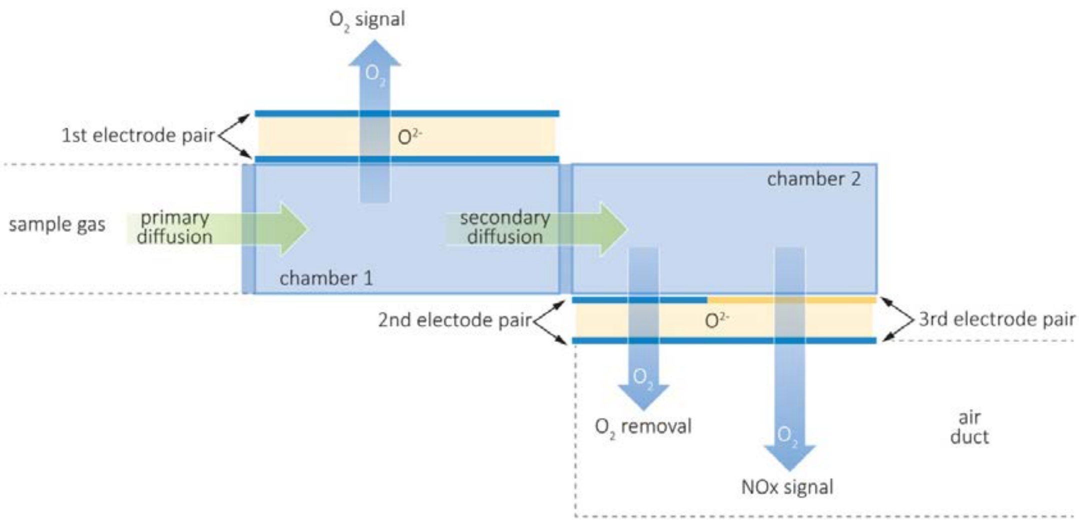

Figure 28 A commercial NOx sensor based on amperometric cells and oxygen pumping (DeBarber and Mizutani, 2011)

Mixed potential sensors for NOx, CO, and SOx

Although widely used in fuel efficient vehicles, this commercial design is complex, difficult to miniaturise, and can suffer from membrane clogging and poor control of oxygen concentration. Academic research has instead focused on the use of mixed potential cells, where the zirconia cell is operated in a kinetically-controlled state, during which competing oxidation and reduction reactions of multiple species contribute to the cell potential, including NOx and the reducing gases (Fergus, 2006; Liu and others, 2014b; Miura and others, 2014) (Figure 29). This is in contrast to equilibrium potentiometric or 'Nernstian' sensors, which simply measure the potential across the cell at electrochemical equilibrium. In a mixed potential gas sensor, one of the standard catalytic Pt electrodes is replaced with a 'sensing electrode', made from a non-catalytic material such as a metal oxide or gold, where the reaction of the target gas takes place. As the gas selectivity and performance of the sensor are largely determined by the characteristics of this electrode, much of the research into mixed potential devices has gone into screening electrode materials. Whilst early work on mixed potential NOx sensors identified oxides such as

WO_3 and $NiCr_2O_4$ as suitable up to 700°C, current research has focused on NiO and its composites, viable for temperatures over 800°C (Lu and others, 2000; Zhuiykov and others, 2001; Elumalai and Miura, 2005). An inherent challenge for NOx sensors is the separate responses for NO and NO_2, which actually give opposite potentials in mixed potential devices, thus cancelling each other out and introducing inaccuracy. The addition of an oxidation catalyst to the sensing electrode can help counter this by converting NO to NO_2.

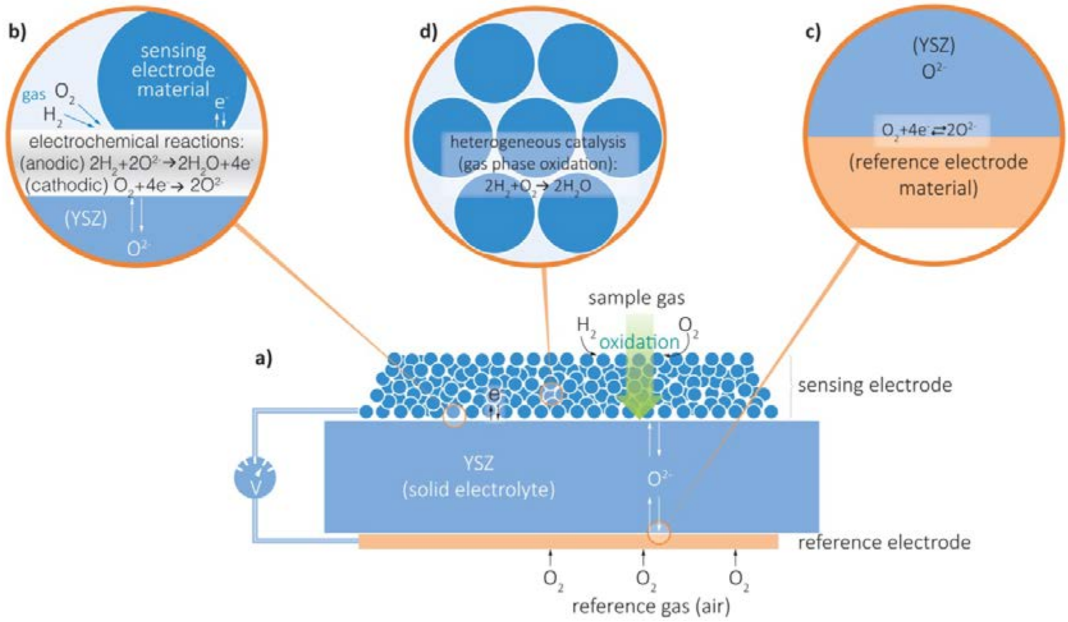

Figure 29 Schematic of the basic structure and principle of a mixed potential YSZ sensor, showing H_2 sensing (Miura and others, 2014)

Mixed potential sensors have also been used for detecting the combustion products CO and hydrocarbon gases, for which the principal challenge is achieving selectivity for just one of these reducing gases (Liu and others, 2014b). Again, a wide range of sensing electrode materials have been tested for their selectivity and performance at high temperatures, including simple metal oxides, oxide composites with gold, and perovskites. For hydrocarbons, it is important to use a material with very low catalytic activity for oxidation, and gold composites with Nb_2O_5 and Ga_2O_3 have shown a good response up to 700°C (Zosel and others, 2002). Sensing electrodes for CO detection up to 700°C include perovskites and a ScSz composite with indium tin oxide, but CO sensors generally suffer from interference from CH_4, NO_2, and O_2 (Li and Kale, 2006; Brosha and others, 2002). To counter this, dual responses from two separate electrode materials can be used, or even arrays of separate sensors as described above (Liu and others, 2014b).

Mixed potential sensors have also been investigated for SOx detection, as an alternative to the extractive and costly UV fluorescence technique conventionally used in emissions monitoring. A YSZ-based device using perovskite sensing electrodes (LSF and LSM) was able to detect 2 ppm of SO_2 up to 900°C (West and others, 2008).

As the cell response is governed by kinetics at the so-called 'three phase boundary' between gas, electrode, and electrolyte, increasing the surface area of this region is one approach to improving device performance, leading to the use of micro- or nanostructured electrodes and electrolyte materials (Liu and others, 2014b). Corroding the YSZ surface with hydrofluoric acid is a straightforward route to increasing surface area, or fabricating more porous electrolytes (Liang and others, 2011; Yin and others, 2013). Electrode materials can be nanostructured by using composites with gold nanoparticles. However, a fundamental limit on mixed potential sensors at high temperature is that chemical reactions tend towards equilibrium with increasing temperature, so the kinetically-limited response of mixed potential sensors also becomes weaker (Sun and others, 2014).

Impedancimetric

A more recent technique to be applied to solid-state electrolyte sensors is the impedancimetric measurement, in which AC voltages of varying frequency are applied to the cell and the impedance taken as the ratio of the voltage to the current in the frequency domain. Impendancimetric sensors have been tested for most combustion gases of interest, but they are of particular interest for NOx sensing, due to their similar response to NO and NO_2 which allows straightforward measurement of total NOx (Liu and others, 2014b; Rheaume and Pisano, 2011). A device with a $ZnCr_2O_4$ sensing electrode has been operated up to 700°C, and the addition of Pt to the electrode can reduce interference from CO by catalysing its oxidation (Miura and others, 2006). However, the effect of varying oxygen levels is a major challenge for this kind of sensor, although measures such as applying two frequencies at once are able to compensate for oxygen to some extent (Martin and others, 2007). Other inherent problems include the relative complexity of electronics and signal processing required relative to other sensor types.

6.1.2 Conductometric sensors

Conductometric or chemiresistive gas sensors employ semiconducting metal oxides whose resistance is reduced by the surface absorption of oxygen due to its effect on oxide vacancy conduction pathways. In a typical configuration, a thin or thick porous film of the material is deposited over electrodes on an inert substrate (Wang and others, 2010). When a voltage is applied across the film, the resulting current can be correlated with oxygen concentration in the surrounding gas. Reducing gases such as CO and CH_4 can also be measured due to their reverse effect on oxygen vacancy concentration in the material. Promoting selectivity for a particular gas is one of the main challenges of these devices, and the performances of numerous metal oxide materials have been tested, with rapid response time another key requirement. However, with their simple design and straightforward fabrication, these sensors offer considerable potential as a lower cost, more robust, and easily miniaturised alternative to solid-electrolyte sensors for combustion (Moos and others, 2009; Liu and others, 2014b; Richter and Fritze, 2014).

Oxide materials which have been successfully demonstrated in conductometric oxygen sensors up to 1000°C include TiO_2, Ge_2O_3, Ga_2O_3, and CeO_2 (Liu and others, 2014b; Ramana and others,

2013) (Table 6). Ceria possesses additional advantages of a rapid response time and a high resistance to corrosive gases such as SO_2 and Cl_2 (Varhegyi and others, 1994). For even higher temperature operation, the perovskite $SrTiO_3$ is a possibility, as it is stable up to 1400°C (Menesklou and others, 1999). A disadvantage common to all these materials is that the film conductivity also has a high temperature dependence which interferes with their response to gas concentration. Some perovskites, such as $SrTiFeO_3$, show temperature-independent O_2 conductivity, but this material is also prone to poisoning by SO_2. Alternatively, an additional temperature compensating material can be used in conjunction with a simple oxide device, requiring a material with a similar temperature response but no oxygen response (Liu and others, 2014b). Examples include ytrria- or zirconia-doped ceria. More recently, the mixed-conducting perovskite LBCO has been demonstrated in conductometric sensors which show extremely rapid response to both O_2 and H_2 at 800°C (Enriquez and others, 2013).

Table 6 Properties of metal oxide materials suitable for high temperature oxygen sensors (Liu and others, 2014b)

Material	Operating temperature (°C)	Detection limit range	Response time
CeO_2	700–1100	–	5–10 ms
CeO_2 (Pt)	615–1000	10^3 to 10^5 Pa	5–11 s
Ga_2O_3	1000	0–100%	10 s
Nb_2O_5 (TiO_2)	550–750	0.01–100 kPa	~5 min
TiO_2	600–1000	10^{-21} to 10^3 atm	–
$SrTiO_3$	750–950	10^{-13} to 10^5 Pa	<30 s

Conductometric sensors for reducing gases based on SnO_2, known as Taguchi sensors, are widespread, but rely on surface adsorption and are not suitable for temperatures over 500°C, at which bulk oxygen also takes part in reactions (Figure 30). At these higher temperatures, metal oxides with much lower conductivities such as Ge_2O_3 and CeO_2 are more suitable, but producing an accurate and stable device still presents a considerable challenge. Sensitivity tends to decrease with increasing temperature, and attaining selectivity between CO and hydrocarbon gases is again difficult. Increasing the surface area for gas adsorption by micro- or nanostructuring the metal oxide is a key technique for enhancing high temperature sensitivity, with dispersions of gold nanoparticles in Ga_2O_3 and CeO_2 nanofibres both showing good sensitivity for CO up to 1000°C (Schwebel and others, 1998; Liu and others, 2012) (Table 7). An effective means of enhancing selectivity for CO over hydrocarbons is the addition of CuO to the film to act as a catalyst for hydrocarbon oxidation. Conversely, a hydrocarbon selective sensor has been demonstrated in which all combustible gases are completely oxidised, and only the water product from hydrocarbons detected (Trimboli and Dutta, 2004).

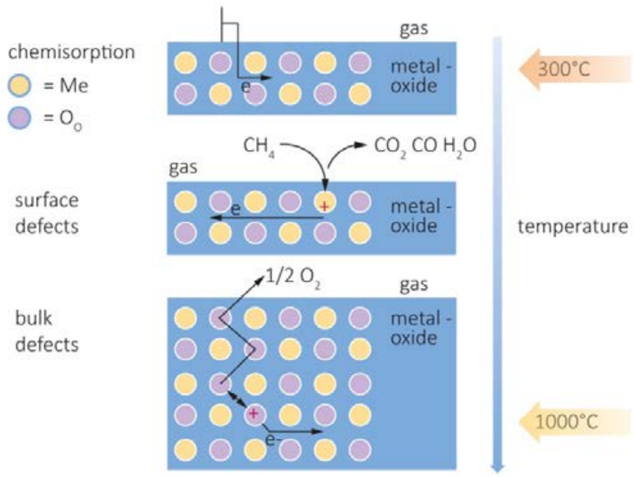

Figure 30 Change in sensing mechanism of conductometric gas sensors with increasing temperature (Liu and others, 2014b)

Table 7 The sensing performance of conductometric sensors towards CO (>600°C) (Liu and others, 2014b)

Material	Carrier gas	Operating temperature (°C)	Detection limit range
$BaSnO_3$	Dry 20% O_2	550–950	0–5 vol%
Ga_2O_3 (Au)	Wet air	500–700	200–5000 ppm
TiO_2 (La_2O_3, CuO)	5% O_2	600	0–1500 ppm
TiO_2 (Pt, Cr)	5% O_2	500–1000	0–1500 ppm
CeO_2	N_2	800, 1000	100– 800 ppm

Some conductometric sensors based on WO_3 have been investigated for NOx, but have so far shown poor stability and selectivity (Ponzoni and others, 2006). Conductometric sensors based on WO3 are also being investigated for H_2S sensing in gasifier applications (NETL, 2014).

The NETL Office of Research and Development is conducting ongoing research towards identifying new high-performance metal oxide materials for conductometric gas sensors, concentrating on simple oxides with nanometer grain size and plasmonic nanocomposites such as gold dispersions in TiO_2 (NETL, 2012).

Dual mode sensors

Both the chemiresistive and potentiometric gas sensor modes have been combined in a single sensing platform for oxygen detection at temperatures of up to 800°C (Sun and others, 2014). In this design, the sensing electrode of a standard YSZ potentiometric sensor is essentially made to double-up as a metal oxide conductometric sensor. The sensing electrode material consists of a thin film of NiO nanoparticles, whilst the reference electrode is the more usual Pt paste.

Combining both sensor types in this fashion allows for a versatile device which can exploit the advantages of both mechanisms, and use the combined readings to improve accuracy.

6.1.3 Microresonant sensors

Resonant gas sensors combine a gas sensitive metal oxide layer with a piezoelectric material whose resonant frequency of vibration under an applied voltage is altered by the presence of an adsorbed layer of gas molecules. Standard devices based on quartz or lithium niobate piezoelectrics are unsuitable for high temperature applications, for which the material langasite ($La_3Ga_5SiO_{14}$) has been identified as the most promising candidate, although $GaPO_4$ and oxyborates are other possibilities (Seh, 2005; Richter and others, 2009; Richter and Fritze, 2014). Two varieties of resonant sensor can be distinguished: In bulk acoustic wave resonators, the entire piezoelectric crystal is excited, whereas in surface acoustic wave resonators, interdigitated electrodes on the crystal surface are used to excite only surface vibrations. The latter variety has attracted the most interest for harsh environment sensing applications due to the possibility of wirelessly exciting the higher frequency surface waves with radio waves (*see* Section 7.2.1).

The sensitivity of these devices is extremely high, with even sub-monolayers of adsorbed gas within the limits of detection. An oxygen sensor based on a thin film of CeO_2 on a bulk langasite resonator could detect oxygen partial pressures down to 10^{-17} bar at 900°C. By distinguishing between the resonant frequencies associated with different gases, the same device can be used to selectively sense CO and H_2 (Richter and Fritze, 2014).

SAW sensors can also be used to measure pressure, strain, torque, and temperature as all these phenomena can induce a change in length along the surface of the device. Temperature sensing requires a piezoelectric substrate with a relatively high coefficient of thermal expansion along its length, whilst pressure is sensed by placing the device on a diaphragm between the environment and a reference cavity at fixed pressure. However, the response of the device to multiple parameters can cause issues of cross-sensitivity.

6.2 High temperature silicon-based sensors

Conventional microelectronic devices are almost entirely based on semiconductor microfabrication, in which semiconducting features (usually doped silicon) are lithographically patterned on to a silicon substrate. Besides its well-known role in the integrated circuits in microchips, this technology can also be used to fabricate transducers for parameters including temperature, strain, pressure, and gas concentrations; often broadly referred to as microelectromechanical systems (MEMS). However, silicon-based devices are unsuitable for use at temperatures much over 350°C, at which severe material degradation starts to occur (Zhao and others, 2014). The ceramic material SiC has been widely investigated as an alternative to silicon devices for high temperature and harsh environment applications. Compared to silicon, SiC has a superior resistance to oxidation and radiation, and its higher bandgap (3.2 eV) reduces the number of thermally activated charge carriers and allows for high temperature operation (Wright and Horsfall, 2007). On the other hand, its low reactivity also renders conventional chemical etching techniques ineffective and makes fabrication of complex structures much more challenging than for silicon, although the development of new techniques such as deep reactive ion etching (DRIE) has greatly expanded the potential for SiC-based devices (Hunter and others, 2006). Beginning in the 1990s, research into SiC devices has been conducted primarily by NASA, Kulite Semiconductors, and Honeywell, leading to a number of commercial devices operational to over 300°C, as well as laboratory demonstrations at over 600°C.

Polymer-derived ceramics (PDCs) are a more recently developed class of silicon ceramics which offer several advantages for use in high temperature MEMS devices. These silicon carbonitride materials are synthesised from liquid polymer precursors, in which the polymer is first thermoset, then crosslinked at over 400°C, before a high temperature pyrolysis step at over 1000°C to form a hard ceramic. This unique synthesis allows for highly versatile fabrication techniques such as soft lithography, direct-write, and micromoulding, where the solid ceramic is formed only after the device is shaped. Most importantly, PDC is stable to over 1800°C and has a superior creep resistance and oxidation rate to SiC, allowing it to be used in even more demanding combustion environments (Zhao and others, 2014; Xu, 2006). The electrical properties of PDCs can be tailored by adjusting the composition of the precursor polymer or the synthesis procedure, with properties ranging from extremely high piezoresistivity to piezo-dielectric materials offering high potential for sensor applications.

Besides fabrication of the transducer itself, a significant benefit of more temperature resistant microelectronics is the potential for closely integrating signal processing electronics on the same chip as a high temperature transducer. Silicon-based MEMS can even be used to fabricate 'micro hotplates' which maintain metal oxide films at the optimum temperature for sensing (Semancik and others, 2001).

6.2.1 Temperature and pressure sensors

Like many semiconductors, the resistance of SiC decreases with temperature, enabling the material to be used in negative thermistor devices for temperature sensing. SiC temperature sensing from 25–400°C has been demonstrated using polycrystalline films formed by chemical vapour deposition combined with electrodes of Al or W (de Vasconcelos and others, 2000; Casady and others, 1996).

The PDC material SiAlCN has also been used for temperature sensors stable up to 830°C (Zhao and others, 2014). Based on a rectangular disc of the ceramic overlaid with Pt electrodes, this device showed a monotonic reduction in resistance with temperature. SiAlCN ceramic has also been used in heat flux sensors based on the gradient method, where PDC thermistors are placed either side of a thermal resistance layer and the temperature gradient monitored (Nagaiah and others, 2006).

Pressure sensors are often based on thin diaphragm structures which are depressed as pressure increases. Movement of the diaphragm can be detected by changes in capacitance of the space between diaphragm and substrate or, more commonly, by piezoresistive thin film strain sensors on the diaphragm surface. Piezoresistivity describes the change in resistance displayed by most materials, which is particularly pronounced in some semiconductors, including SiC and PDCs. Although the fabrication of diaphragms in SiC is challenging due to the difficulty in controlling etch depth, a combination of DRIE and electrochemical etching has enabled piezoresistive-type SiC pressure sensors which are stable up to 600°C (Hunter and others, 2006; Ned and others, 2004) (Figure 31). However, most commercial SiC sensor designs still include Si for some components and are only stable to 300°C (Kulite, 2004). PDCs which show a strain-dependent permittivity known as the piezo-dielectric effect have been used in wireless strain sensors (Cao, 2014) (*see* Section 7.2.1).

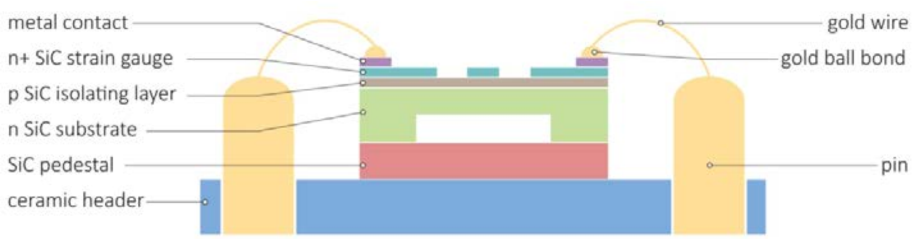

Figure 31 A schematic of a SiC-based diaphragm pressure sensor (Hunter and others, 2006)

For all high-temperature silicon-based devices, the stability of the metal contacts through which the device is connected to controller electronics. Conventionally used materials such as Pt, Au, and Pt-Pd alloys can react with the substrate or dewet at high temperatures, so identification of suitable alternatives is required. The use of layered alloys such as Ti/TaSi2/Pt has proved successful for up to 600°C (Hunter and others, 2006). The devices are typically protected from the environment by an overlay of more Si ceramic material.

SiC has also been used in commercial photodetector diodes for high-temperature optical sensing applications. The high band gap of the material means that only radiation of wavelengths below 365 nm (UV) can be detected.

6.2.2 Field effect transistor gas sensors

Field effect transistors (FETs) are the silicon-based microelectronic devices at the heart of modern electronics. Essentially acting as electrically-activated switches, the current allowed to pass through a semiconducting channel between two electrodes is controlled by a third 'gate' electrode. When a gas sensitive catalyst layer is applied to the gate electrode, FETs can function as gas sensors as the electrical potential generated by gas adsorption acts as an additional gate voltage and alters the current. A relatively recent development in gas sensing, these sensors have been subject to much research interest, due to an unprecedented range of sensing materials which can be integrated with the FET (Moos and others, 2009).

FET gas sensors using silicon carbide have been developed at Linkoping University for sensing almost all combustion relevant gases including SO_2, H_2, CO, O_2, NOx and NH_3 (Ali and others, 2006; Darmastuti and others, 2013; Spetz and others, 2013; Andersson and others, 2013). These 'depletion-mode' transistors have the added benefit of requiring minimal applied voltages to operate, lowering energy consumption and improving the stability of the catalytic metal. SO_2 sensing poses a particular challenge as it is an effective catalyst poison which is difficult to desorb from the catalyst once adsorbed. This results in low response levels and saturation of the device even at low levels of SO_2. However, intermittent exposure to high temperature can help desorb the gas from the sensor (Darmastuti, 2014). These devices operate in the 300–400°C range and so are not suitable for some of the high temperature applications targeted by the other sensors in this section. However, they could prove effective for lower temperature applications in pollutant control, such as sensing ammonia slip for SCR units, and SO_2 to determine desulphurisation dosages. A particulate sensor of similar design has also been developed (Spetz and others, 2009).

6.3 Metallic thin film sensors

Miniaturised temperature sensors can also be based on the thermocouple format, as the dissimilar metal junction can be miniaturised to the scale of thin films deposited on the surface of interest. This kind of device is frequently deployed on gas turbine blades (for research purposes rather than during field operation), where there is a need for sensors which interfere minimally with air flow and blade mass, yet maintain stability at very high temperatures. As for larger-scale thermocouples, platinum and rhodium are suitable metals for high temperature operation up to 2000°C, and thin film devices are typically based on a junction between PtRh alloy and pure Pt. The metals are deposited and patterned using sputtering and lithography techniques, after having first deposited an alumina layer to provide electrical insulation from the material of interest.

Similar fabrication techniques can be used to deposit thin film strain gauges on turbine blades. These devices use the strain-dependent resistance of a palladium-chromium alloy which is also stable to 1100°C and can undergo repeated strain and temperature cycling. The more complicated structure requires a chemical etching step (NASA, 2007).

Being mounted on rotating parts, both of these devices require connection to external instrumentation via a slip-ring contact which introduces significant noise and is prone to failure, A principal research direction is to develop wireless temperature and strain sensors which could be used during field operation of turbines, discussed in the following chapter.

7 Wireless sensor networks

The increasing availability of low cost, miniaturised sensors introduces the possibility of deploying large sensor networks throughout a power plant, maximising the amount of online data available for the increasingly demanding requirements of plant control and monitoring. However, to avoid being severely limited by the additional cost, vulnerability, and weight of wiring, such a network is obliged to use wireless communication technology, which also permits sensor placement in harsh environments, rotating equipment, and other inaccessible locations. Wireless networking of conventional sensors has seen growing adoption for power plants in the last decade, although almost exclusively for monitoring parameters such as temperature, pressure, and level, rather than control purposes (Thusu, 2010; Taft, 2010; Hitchin, 2014). To accompany this growth, considerable progress has already been made in developing wireless networking technologies suited to the industrial environment, including new wireless communication protocols, secure networks, and the use of flexible 'mesh' network topologies. As these networks increase in size and begin to make use of miniaturised and 'smart' devices, there is a need for new computational approaches for organising the large amounts of data generated. Self-organising networks which handle data intelligently can be greater than the sum of their parts, providing hugely enhanced tracking of plant parameters even when the individual sensors themselves are relatively inaccurate. Such distributed sensor networks could be the next step in control of complex power systems which are too demanding for computational modelling (Mukhopadhyay and Leung, 2010; NETL, 2013).

Power supply becomes a critical consideration for wireless devices, and networks must be organised to minimise the power used in sensing and data transmission. As an alternative to conventional battery-powered devices, which have limited temperature resistance and require eventual replacement, methods for battery-free, wirelessly powered devices have been developed. These include using the radio frequency communication signal itself as a power source and 'harvesting' ambient energy such as heat and vibration.

7.1 Considerations for wireless networking

Wireless sensor networks consist of a collection of communication nodes which each comprise a radio transceiver, microcontroller, and energy source, and can be associated with one or more sensors. In power plants, wireless nodes typically communicate using the same license-free 2.4 GHz radio-frequency bandwidth used by WiFi devices, but using specially adapted industry-specific networking protocols. A number of wireless protocols have been developed, with WirelessHART and ISA100.11a the leading products, resulting in similar issues of device compatibility created by the array of protocols available for wired networks. Network security becomes an important consideration for wireless networks, and most protocols are equipped with a stringent set of encryption and authentication measures (van der Brent, ND; Taft, 2010; Berge, 2011).

Sensor data collected by each node must be transmitted to a wired collection station, but the manner in which this is performed is dictated by network topology. 'Mesh' topologies, in which data can take any route through the network to the collection point, are generally adopted by wireless networks in industry, due to the increased flexibility and range they offer (Figure 32). In a mesh network, nodes are programmed with software which enables them to choose the quickest and most reliable path for routing data, allowing the path to adapt to constantly changing elements of the plant environment such as sources of electromagnetic noise and temporary obstructions. The network is 'self-healing', meaning that data are easily rerouted if a node is damaged and goes offline, and by the same token, can be easily scaled up or down. Mesh networks also help route data around permanent obstructions such as boilers, which would otherwise dramatically reduce wireless range (van der Brent, ND; Taft, 2010; Bourdenas, 2011). Research into improving wireless network protocols for industrial purposes was the focus of an EU-funded project 'GINSENG', completed in 2012 (European Commission, 2008).

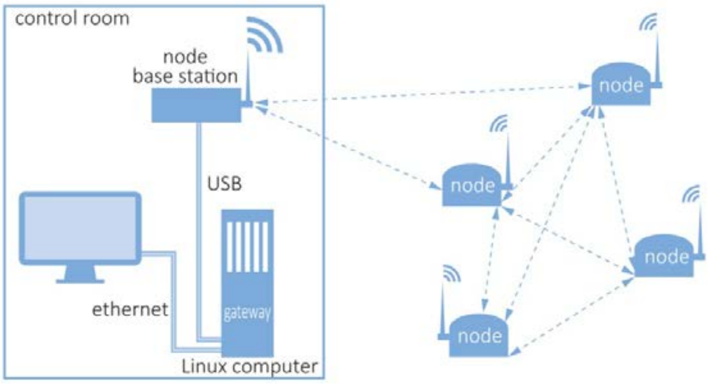

Figure 32 A wireless mesh network (Taft, 2010)

The power of the network can be enhanced by smarter devices, capable of intelligently responding to data from surrounding sensors and using it to provide more useful information or economise on transmission power. For example, neighbouring sensors which register similar values of a parameter can take an average, or ignore redundant readings until significant variation arises.

Commercial wireless sensors are usually integrated with communication hardware to form a single network node. The technology used for the sensor itself is not restricted, and can include optical fibre sensors (Liu and others, 2012). Some of most beneficial attributes for wireless devices include (Thusu, 2010):

- adequate transmission range;
- provide a secure radio frequency signal;
- self-locating;
- self-calibrating and self-configured;
- self-powered or adequate battery life;

- multi-vendor interoperability;
- miniaturised sensors.

Wireless sensor networks are currently used primarily for validation of new equipment, plant diagnostics and performance testing, or safety monitoring such as hazardous gas levels. In this respect, they frequently serve as a low cost alternative to field inspections. However, as confidence in wireless devices grows, they will see increasing use in plant control. Although, PID control loops are still a challenge for existing network speeds, relatively slow or open loop control tasks are well within their capabilities, and could therefore represent a first step for the technology in process control applications (Berge, 2011).

7.2 Wireless power supply

Current commercial wireless devices use high power, long lasting batteries, with a wide range of operating temperatures, such as the lithium thionyl chloride battery. Minimising power consumption is nevertheless a key concern for wireless sensors, and the network should be optimised with this constraint. For example, to avoid unnecessary data transmissions which waste energy, sensors can transmit only when some critical variation in the monitored parameter is reached (Berge, 2011).

To allow greater independence from finite energy supply and increase the potential for miniaturised and robust devices, novel technologies for battery-free devices have been developed. Passive sensors, such as thermocouples, generate their own signal which can be amplified and transmitted without any power supply. This concept has been extended to temperature monitoring of turbine blades by using thin film thermocouples and high-temperature SiC electronics for the signal processing and transmission (Yang, 2013). Active sensors, on the other hand, require their own power supply which can be derived from either the interrogating radio frequency signal or 'energy-harvesting' of various sources of ambient energy. However, these devices may also employ a backup thin film battery for occasions when environmental conditions are unfavourable.

7.2.1 Radio frequency-powered sensors

As energy harvesters are often complex and provide very small amounts of power, radio-powered devices have been the subject of considerable attention for use in inaccessible, high-temperature environments, or on rotating machinery such as gas turbine rotors. The basic elements of such devices have been drawn in large part from developments in radio frequency identification technology (RFID), originally directed simply at tracking and identifying objects. In passive RFID, the tracked device uses power from the interrogating signal itself to transmit back from its own transponder, potentially also modulating the return signal with information from the device (Cook and others, 2014). This requires the interrogating signal to be several orders of magnitude more powerful than needed for signal transmission alone, so high frequency radio waves are used. If integrated with a transceiver radio antenna, a sensor with relatively low power requirement can act as a passive RFID device which transmits a radio signal with the sensor response encoded in the form of frequency or phase.

Whilst a number of radio-powered sensors of this nature have been commercialised, relatively few are capable of withstanding high temperatures, and this remains an active research area. Development of wireless temperature and strain sensors for control and condition monitoring of gas turbines is of particular interest in the fossil fuel industry. Wired thin film thermocouples and strain sensors on rotating parts of a turbine require connection via slip ring devices, which are unreliable and introduce signal losses (Yang, 2013). Temperature measurements by optical pyrometry are a highly accurate alternative, but can only average over an entire rotating diameter, rather than focusing on a specific location on the rotating part.

Wireless surface acoustic wave sensors

As discussed in Section 6.1.3, resonant sensors using surface acoustic waves (SAW) are highly suitable for wireless powering, as the piezoelectric acoustic wave can be excited by high frequency radio signals. Commercial wireless sensors of this type include products from Senseor and Sengenuity, which can operate to 165°C and 120°C respectively, and are aimed at applications such as food processing and medicine. However, research performed by the University of Maine and the associated spin-off Environetix, has developed a wirelessly-powered SAW sensor specifically for temperature measurements in high-temperature power plant applications, with potential for additional pressure and gas sensing (Perreira and Maskay, 2014). The device consists of a langasite piezoelectric crystal, on the surface of which are deposited two sets of interdigitated transducer electrodes connected to a helical antenna (Figure 33). An interrogating radio signal induces a SAW in the sensor which is reflected back to the electrodes with information about the crystal temperature. This signal is converted back to a radio frequency signal in which frequency changes correlated to temperature fluctuations in the device.

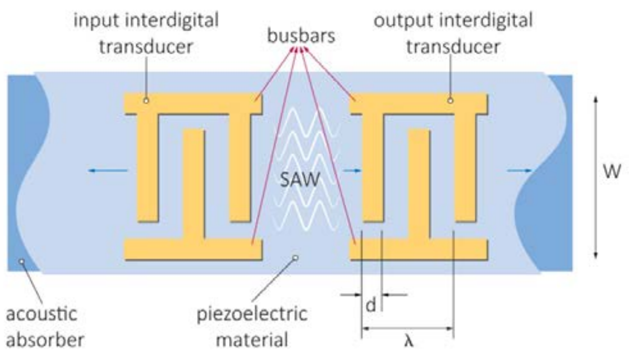

Figure 33 Design of a wirelessly powered surface acoustic wave temperature sensor (Perreira and Maskay, 2014)

A principal technical challenge in producing a SAW sensor stable to high temperatures is identifying a suitable electrode material, as platinum, the conventional choice, 'dewets' from the crystal surface at 700°C. Instead, the research has developed PtRh/ZrO_2 electrodes which are suitable up to 850°C, and is currently identifying materials viable up to 100°C. The sensor has been trialled under several power plant conditions, including in a gas combustor test facility with gas temperatures up to 1100°C, and under highly corrosive conditions in the economiser area of a municipal solid waste furnace. The devices remained operational and temperature readings were closely verified by an adjacent thermocouple.

Dielectric resonators

An electrical circuit incorporating an inductor and a capacitor can acts as an electrical resonator used for generating or selecting radio signals of a particular frequency. If the permittivity of the dielectric material used in the capacitor has some dependence on physical parameters of the environment, this will also be expressed in the resonant frequency of the device. This principle has been exploited for several sensors designs with wireless interrogation capability (Gregory and others, 2010; Cao, 2014).

A design from Wireless Sensor Technologies for a high temperature sensor based on this concept is also principally aimed at monitoring gas turbine blade temperature. The device consists of a thin film of dielectric laid on the target substrate (the turbine blade), on top of which is deposited a thin film antenna (Gregory and others, 2010) (Figure 34). A second section of the antenna extends through the dielectric to make electrical contact with the substrate, and a diode is also connected in parallel between the antenna and substrate. The interrogating radio signal generates a voltage across the dielectric which oscillates at a resonant frequency, but also contains harmonic frequencies produced by the diode which relate to temperature-dependent characteristics of the dielectric. This modulated signal is re-transmitted by the antenna and detected.

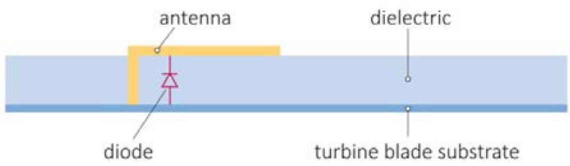

Figure 34 wireless thin film temperature sensor from Wireless Sensor Technologies (Gregory and others, 2010)

A project at the University of Central Florida has used the piezo-dielectric properties of polymer-derived ceramics to develop a wireless strain sensor also based on a radio frequency resonator (Cao, 2014).

Despite the technical challenge posed by energy-harvesting sensors, they have also been the subject of significant research, with power plant applications offering a particularly suitable environment due to abundant thermal and vibrational energy. Energy-harvesters can be categorised by the form of energy they use, as well as the transduction mechanism by which it is converted to electrical power.

Thermoelectric generators

The thermoelectric or Seebeck effect describes the voltage which accompanies a thermal gradient between two dissimilar conductors, widely known for its application in thermocouples. Thermoelectric generator devices designed to draw electric power from this effect were originally also based on bimetallic junctions, but now instead employ a pair of doped semiconductor materials: one n-type (electron conducting) and one p-type (hole conducting). Semiconductors are preferable as, unlike metals, their electrical conductivity can increase with temperature. However, even the highest-performance materials have an energy conversion efficiency of less than 10%.

Some research has been conducted into sensors powered by thermoelectric generators for high temperature and power plant environments (Kuchle and Love, 2013). Wireless Sensor Technologies are developing a system aimed at condition monitoring of gas turbine blades up to 1000°C, and which will operate as part of a wireless sensor network (NETL, 2012). The sensors will include thin film temperature sensors and passive heat-flux sensors to monitor the integrity of the thermal barrier coating. Research at the University of Washington is concentrating on identifying p-type semiconductor materials which match the thermoelectric performance of well-established n-type materials, as well as showing good stability at high temperatures (NETL, 2012). Shi and others have also developed a wireless temperature sensor powered by four thermoelectric generators (Shi and others, 2014).

Thermionic devices

Thermionic emissions describe the heat-induced flow of charge carriers over a potential barrier, such as in escaping the conductor entirely, or in passing from one solid-state material to another. Thermionic converters use this effect to produce useful electric power, and comprise a hot electrode from which electrons pass to a cooler electrode.

PARC are a company developing a self-powered thermionic sensor for temperature or pressure which can be used in temperatures up to 1600°C (Sahu and others, 2014). Power for the device is generated by a thermionic voltage created in a BaO thin film placed between a hot cathode, exposed to the high temperature environment, and a cold (300°C) cathode adjacent to a heat sink. The sensing elements are thin films fabricated from the thermionic material tungsten, or a La-W composite. Temperature sensing is simply provided by the temperature-dependent thermionic current generated in the film, whilst a diaphragm arrangement is used for pressure sensing. As the diaphragm is depressed, the electrodes are pushed closer together, increasing the thermionic current between them. The whole device is given high temperature stability by encasing in a monolithic ceramic support structure.

Vibrational energy harvesting with piezoelectrics

Vibrational kinetic energy can be harvested by a number of transduction mechanisms, including electromagnetic induction and piezoelectrics, both of which have seen relatively widespread commercial application (Zuo and Tang, 2013). Piezolectric materials, which generate a voltage upon mechanical deformation, have the most potential for miniaturisation and integration with wireless devices in power plants. The ceramic lead zirconate titanate is one of the higher-performance piezoelectrics for energy-harvesting, and output power can be increased by stacking wafers or grouping them in arrays. However, as the energy produced is still small, these devices have been primarily considered for storing up energy over time and using it to recharge a battery (Sodano and Inman, 2005). Nevertheless, Cerametrics are one commercial supplier who have developed a self-powered wireless sensor system based on harvesting mechanical energy, using a composite material containing piezoelectric fibres which produce electricity from vibration or shock. The device can harness forces of up to 1 kg and operate in temperatures up to 150°C (Cerametrics, ND).

7.3 Distributed sensor networks

Distributed sensor networks constitute an alternative approach to sensing, where individual, reliable sensors are replaced with a dense network of low cost and potentially unreliable sensors which organise themselves to be collectively capable of more complex tasks (Iyengar and Brooks, 2005). They have been the subject of research since the early 1990s for use in a wide range of applications including terrain mapping and robotics, and have more recently been investigated for use in power plant control and monitoring (Clare and others, 1999). As communication between sensors is essential, wireless sensor networks are well-suited to distributed sensing, and smarter sensors with integrated processing power can also increase the potential of the network for self-organisation. Individual sensors can take decisions on whether to sense or 'sleep' at a given time, governed by an aggregating function which seeks to achieve an objective for the whole network such as minimising its energy consumption or maximising accuracy of the signals and reducing noise. This effectively optimises use of the network by, for example, preventing sensors which are providing noisy or redundant data from remaining active and wasting energy. In cases where the data generated is fed to a control system, the network may even be given a controlled variable of the system, such as efficiency, as its objective.

Self-organisation of sensor networks relies on complex algorithms for performance assessment and optimisation, often inspired by biological systems amongst which higher level, emergent behaviour from simple rules is widespread. For example, research at Oregon State University has employed an 'evolutionary algorithm' as an optimisation strategy for sensor networks in power plants (Tumer, 2014; Colby and Tumer, 2012). The network performs a series of trials based on a probability distribution of individual sensor actions and their performance is assessed with respect to an objective. The best performing combinations of sensor actions are then randomly altered ('mutated') before being reassessed and selected, with the process continuing until the objective is optimised. In order to ensure that sensors don't work at cross purposes, but all contribute to the system, performance is assessed via both a global objective function and a local objective at the level of each sensor. Essentially the sensor has to evaluate whether optimising its own objective is also good for the entire system, using a difference evaluation function as the mathematical device to align the two objectives. This learning algorithm approach was used to significantly increase the accuracy of a model network of unreliable temperature and pressure sensors, used to estimate enthalpy in a Rankine cycle. This trial also demonstrates the inherent flexibility of such self-organising systems, as accurate readings could be re-established by the network even after introducing 20% noise or 20% sensor failures.

Other research has made use of principles from information theory to help quantify the usefulness of data generated by the sensor network (Loparo, 2014). This analysis can help the network perform tasks such as fusing information from several sensors, reconstituting lost or degraded observations, and detecting system changes.

These principles of network self-organisation and optimisation can also be applied to controllers themselves, enabling control decisions to be completely decentralised and therefore more efficient. Individual controllers act collectively to optimise an objective function, adapting their response using information from other controllers and optimisation algorithms which can again be drawn from biological systems (NETL, 2014). The NETL has identified this kind of control strategy as an effective solution for power systems of increasing complexity which may defy system modelling.

7.4 Optimising sensor placement

When deploying a large wireless network, the positioning of each sensor can be optimised to maximise system coverage, improve communication, or minimise energy consumption. Most research in this area is targeted at finding the node arrangement which minimises the distance travelled by data and thus the energy consumption of the network (Younis and Akkaya, 2008). This in itself is a complex problem which requires detailed mathematical analysis (Kar and Banerjee, 2003).

Research by Rengaswamy and others has considered the problem with respect to the optimum placement of sensors for fault detection in a condition monitoring network for an IGCC-precombustion capture plant (Rengaswamy and others, 2014). This requires physical modelling of each plant subsystem, prediction of likely fault locations through literature analysis, and modelling of the effect of system faults on the monitored parameters. As identification of the sensor configuration best-suited to detecting the simulated faults requires searching a huge variable space, an evolutionary algorithm is used to accelerate the search. A network arrangement is altered slightly at each step and assessed with a fitness function based on is fault-detection performance.

8 Conclusions

Improvements to power plant control systems are increasingly recognised as a powerful means of upgrading existing plant to meet the demands of the current energy generation landscape. The ability to maintain an optimum operational state under changing conditions equates to improved flexibility, higher efficiency, and reduced emissions, all potentially contributing an economic benefit to the plant. Combined with the need to meet the new control challenges posed by new high steam temperature plant and IGCC, these incentives have encouraged a growth in research aimed specifically at developing new sensors and control technologies for the fossil fuel sector. This is particularly the case in the USA, where efficiency improvements in the substantial existing coal fleet represent significant economic gains, and a strong IGCC programme has prompted development of more robust sensors for the gasifier and turbine environments. As the control problem can be met both by expanding the sensory data available or improving control algorithms, both these approaches are being pursued by the industry and in research institutes.

Optimisation of the combustion process represents the most significant control challenge faced by large pulverised coal power plants. A delicate balance between the constraints of low NOx emissions and high combustion efficiency must be achieved, all whilst maintaining the correct flue gas temperatures for optimum heat transfer to the steam cycle throughout load changes and other disturbances. In spite of these demands, due to the inhospitable conditions present, furnaces have traditionally been controlled with limited data from relatively few online sensors which are often placed at inadequate locations. Over the last decade, a number of new online monitoring technologies have emerged to fill this knowledge gap and help optimise combustion in real time. One approach is to accurately determine and control coal and air flow to each burner using online flow sensors, with the availability of low cost optics making imaging-based methods increasingly effective. Alternatively, the stoichiometry at each burner may be deduced indirectly from detailed analysis of spectral data or images of the flame itself. Analysis of the combustion products is also needed to accompany such measurements, yet sensors for CO and excess oxygen are often too far from the furnace or too few in number to yield sufficiently accurate flue gas data. The use of tunable diode lasers to perform absorption spectroscopy across a furnace section has emerged as a highly effective means of monitoring gas concentrations and temperatures close to the burners, with laser grids able to generate a complete profile of the relevant parameters.

It is noteworthy that many of the sensor technologies currently making an impact in combustion control are optical methods. In addition to the high selectivity and sensitivity offered by such techniques, handling data signals in an optical form is well-suited to the power plant environment, where high temperatures and electromagnetic noise can be problematic for electronic devices. Of particular interest are devices formed in optical fibres themselves, such as Fabry-Perot interferometers (FPI) and fibre Bragg gratings (FBG), which can act as powerful miniaturised sensors; but research is needed to develop devices robust enough for high temperature combustion or gasification environments. The use of single crystal sapphire fibres has enabled FPI temperature sensors to be used up to 1600°C, whilst femtosecond laser techniques have been used to write FBG temperature and strain sensors viable to over 1000°C. A useful capability of optical fibre sensing is the possibility of distributed sensing, in which a parameter is mapped along the entire fibre length by analysis of backscattered light. In combination with additive manufacturing techniques, such optical fibre-based sensors can also be embedded within power plant components for condition monitoring.

Despite the high performance offered by optical sensing technologies, the availability of low-cost, mass-fabrication techniques developed for the microelectronics industry means there is also great potential for miniaturised solid-state sensors for combustion applications. Partly based on the widespread use of the zirconia oxygen sensor, such devices have been particularly investigated for gas sensing, but new gas-sensitive materials are required to overcome fundamental challenges of poor selectivity and sensitivity at high temperatures. The electrochemical principle of zirconia sensors can be extended to NOx sensing through operation in amperometric or mixed potential modes, although these techniques are respectively limited by high device complexity and poor sensitivity at high temperatures. Impedance measurements are a new technique which is well-suited to NOx sensing but limited by complex signal processing requirements.

Whilst the relative complexity of these zirconia-based devices can be reduced through the use of solid reference cells, a promising alternative is the resistive-type gas sensor based simply on a thin film of metal oxide. These potentially low cost and robust devices have been demonstrated for accurate oxygen sensing to 1000°C, and also show promise for CO despite suffering from cross-sensitivity with other reducing gases. In addition to identification of new materials, advances in this area are being made through increased use of micro- and nanostructured films and interfaces which enhance sensitivity by increasing the reactive surface area. The use of sensor arrays which share a substrate, or even combining different sensor modes in one device, are possible routes to improving selectivity.

Miniaturised optical or electronic sensors are most valuable when combined with the capability for wireless communication, enabling deployment of sensor networks which are not limited by inaccessible locations or the cost and vulnerability of wiring. Whilst communication protocols and network topologies have already been introduced to meet the growing trend in plant monitoring with wireless networks, self-powered, miniaturised wireless sensors are needed to maximise the potential of these networks for control applications. Radio frequency-powered devices based on dielectric resonators or surface acoustic wave sensors are amongst the most promising concepts, with thermal energy-harvesting sensors also under investigation.

As these new sensor technologies send increasing quantities of data to power plant control systems, new approaches may be required for generating the appropriate control responses. In the last twenty years, the power industry has seen increasing adoption of advanced process control techniques which use artificial intelligence and empirical models to solve complex multivariable control problems such as combustion optimisation. Neural networks have proved useful for modelling the nonlinear behaviour of the furnace, but model predictive control is now the dominant force in advanced plant control, thanks to its ability to handle dynamic, rapidly changing variables such as steam temperature during load changes. However, as the processing power in sensors themselves grows, control tasks are increasingly pushed towards the sensor level. Techniques such as model-free adaptive control and enhanced communication between sensors could enable individual microcontrollers to cope with complex system control without higher level supervision. Large networks of wireless sensors allow for new control paradigms based on wholly distributed control, and the use of biologically-inspired algorithms has been investigated for grouping and optimising the individual contributions to the data generated.

Many of the more novel sensor technologies and control strategies addressed here are still in the early stages of development and are unlikely to make a rapid transition to commercial deployment in the power sector. Nevertheless, the industry is seeing increasing application of more advanced sensing techniques including wireless networking, in situ optical methods, and advanced high temperature materials. Equally, the use of advanced control algorithms has been progressively accepted by the power industry as available computing power becomes better matched to the task. Whilst the economic and environmental benefits derived from these improvements to existing plant control systems in the last few years have often been considerable, the next generation of robust sensor technologies to emerge from research laboratories could help facilitate deployment of a new generation of advanced, high efficiency fossil fuel power systems.

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