Optimising fuel flow in pulverised coal and biomass-fired boilers

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Preface

This 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.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, China, the European Commission, Germany, India, Italy, Japan, New Zealand, Poland, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

Poor pulverised fuel (PF) distribution to the burners has a significant, negative effect on combustion efficiency, wear of equipment and emissions, not to mention economics.

The major areas of a power plant where improvements can be made are the mills, air/fuel ratio, pipework and boiler. However, before any optimisation can be achieved, measurements which are not only reliable and repeatable, but ideally in real time, must take place. Only then can accurate control and optimisation of the fuel flow be introduced. All of these are especially important in low NOx burners which require precise fuel control in order to maintain uniform and efficient combustion.

The report looks at major areas where improvements can be made. It reviews recent developments in measurement and control systems for fuel fineness, combustion air streams, air/fuel ratio and the fuel flow distribution. Additionally, it briefly reviews advances in oxygen and carbon monoxide and carbon in ash monitoring and their usefulness in control and optimisation of air and fuel flow. Examples of the optimisation approaches and benefits that these can produce for both pulverised coal and biomass boilers are included.

Acronyms and abbreviations

AFR	air/fuel ratio
AMC	Air Monitoring Corporation
CADM	computer-aided design and manufacturing
CCD	charged coupled device
CCM	continuous management system
CFD	computational fluid dynamics
CFM	Coal Flow Monitoring
CCW	counter clock wise
CW	clock wise
DCS	distributed control system
DMCCO	Delta Measurement and Combustion Controls
dP	differential pressure
DSP	Digital Signal Processing
FD	forced draught
FEGT	furnace exit gas temperature
FGD	flue gas desulphurisation
ESP	electrostatic precipitators
EPRI	Electric Power Research Institute
HGI	Hardgrove Grindability Index
IBAM	Individual Burner Airflow Measurement
LOI	loss on ignition
NOx	nitrogen oxides
OEM	Original Equipment Manufacturer
OFA	overfire air
PA	primary air
P&I	piping and instrumentation diagram
PF	pulverised fuel
ROI	return on investment
RTD	resistance temperature detector
SA	secondary air
SCR	selective catalytic reduction
SP	static pressure
UBC	unburnt carbon
UCA	unburnt carbon-in-ash
TDLAS	tunable diode laser absorption spectroscopy
TP	total pressure

Contents

List of Figures

List of Tables

1 Introduction

Increasingly stringent environmental legislation and an obvious need to be economically viable mean that operators of coal-fired power plants are constantly striving to improve overall plant performance (Rodriguez and others, 2012). As many technologies are available to power plant operators, the fundamental improvement in combustion performance for pulverised fuel fired boilers that air and coal or biomass flow balancing can achieve is frequently overlooked (Estrada and Sisson, 2011). Consequently, opportunities to reduce emissions, carbon-in-ash (LOI), maintenance and operating costs and to eliminate safety hazards are frequently missed.

Lack of fuel flow optimisation creates many problems. For example, high coal flow to burners can create carbon-rich zones with a reducing atmosphere that leads to increased slagging and carbon monoxide (CO) emissions. Burners with too little coal flow can create oxygen-rich zones that may increase emissions of nitrogen oxides (NOx). In addition, a burner which delivers pulverised fuel at too high a velocity not only causes increased erosion of the system and high carbon-in-ash levels but can cause detachment of the flame within the boiler. Pulverised fuel which is delivered at too low a velocity can cause fall out of particulates and create pipe blockages which consequently can create dangerous fires and explosions.

In order to optimise pulverised fuel flow many aspects need to be taken into account. The major areas of a power plant where improvements can be made are the mills, air/fuel ratio, pipework and boiler. However, before any optimisation can be achieved, measurements which are not only reliable and repeatable, but ideally in real time, must take place. Only then can accurate control and optimisation of the fuel flow be introduced. All of these are especially important in low NOx burners which require precise fuel control in order to maintain uniform and efficient combustion.

It has been reported that at least 75–80% of opportunities to improve the combustion performance at most pulverised coal-fired plants are dependent on a reduction in coal particle size. Consequently, combustion and fuel flow optimisation should start with improving particle fineness and mill performance. Before such optimisation takes place – accurate, reliable and real time measurements are necessary. Unfortunately, at the majority of power plants, particle fineness is checked only occasionally – once or twice a year. Furthermore, the dominant measurement method is manual isokinetic sampling. This is not only labour consuming but also has a large error and does not give simultaneous and real time results from all coal pipes. Hence, it cannot be used for the accurate, immediate optimisation of particle fineness and mill performance. Fortunately, recently there has been considerable development in particle fineness measurement systems. These can be applied both to pulverised coal and biomass boilers. Based on a number of operational techniques, such as acoustic emission, electrostatic, laser and white light, most of these technologies allow the simultaneous measurement of particle fineness as well as particles and air velocities and fuel concentration. Most importantly, they provide reliable, real time results. Consequently, the direct modification of coal fineness can take place. This is achieved by a number of ways, including: ensuring the correct/optimal raw coal size and its supply to the mill; keeping mill grinding elements in a good condition; applying the correct grinding pressure; setting the correct throat clearance and air flow; classifier maintenance and maintaining suitable mill inlet and outlet temperatures.

All air flows in a power plant must be measured and controlled in order to achieve optimum combustion at the boiler and avoid problems such as high furnace exit gas temperature, secondary combustion, overheating in the back-pass as well as slagging. However, such air streams are turbulent and stratified, hot, moist and particle laden. This makes air flow measurement not an easy task. Additionally, air ducts to and from different mills have various geometries and lengths which impact air measurement devices, especially the most traditional ones (those used since the 1950s and 1960s), as most of them require sufficient length of straight and plain pipe to be installed. Furthermore, many also require field calibration. Most portable devices used to calibrate these systems require a laminar flow that does not exist in most combustion airflow ducts. Moreover, many devices provide air flow measurements calculated with a constant cross sectional area of a given air duct. However, as air ducts expand and contract under hot and pressurised air streams, their cross section changes. Hence such measurements can have a considerable error. New, more advanced technologies for combustion air flow measurement attempt to deal with all these difficulties. Such systems range from advanced pitot tubes through electrostatic based systems to virtual and optical sensors. They are also more accurate than the old ones and designed to avoid clogging, corrosion and breaking. But all technologies have limitations and care should be taken to read product specifications for restrictions (temperature, flow, particulate, moisture, straight run and more). Importantly, low NOx burners now have a choice of individual burner measurement systems.

Conventionally, coal flow is monitored by the volumetric or gravimetric (to a much lesser extent) feed rate of coal to the mills and is directly dependent on the boiler firing rate and the current load demand of the plant (Lockwood, 2015). As power plants have multiple mills and fuel is transported to the individual burners via geometrically different pipes, it is 'natural' for fuel to take the easiest route (with the lowest pressure drop) to the burner (Greenbank, nd[a]). Unless some kind of fuel flow control devices are in place, uneven fuel distribution, roping and pipe blockages can and will occur. These result in inefficient combustion, high emission levels, and equipment erosion and can also lead to serious consequences such as fires and explosions. Therefore, it is necessary to control and optimise fuel distribution from each mill to its corresponding burners. Such control and consequent optimisation are only possible when accurate, online and real-time measurements take place. As pulverised fuel carried by air is a dynamic, two phase flow in which coal particles move with a different velocity than air, traditional and most commonly isokinetic sampling cannot provide immediate and accurate data necessary for timely combustion optimisation. New systems for coal flow measurement are based on laser, white light, acoustic emission, microwave, electrostatic and mathematical cross-correlation principles. They are much more accurate then manual sampling, give real time feedback and are not labour intensive. As with any type of technology, there are a number of factors affecting their performance. Consequently, before choosing a coal flow measurement system the following need to be considered: whether the equipment can be incorporated into the existing coal pipe geometry and if not what changes are required; operational mode of the equipment (stationary, mobile); the need for, ease of and time required for calibration; scale down and consequent shutting down of the plant; sensitivity of the system to high temperatures and flue gas conditions such as stratification, moisture and different velocities; pipe geometry impact; if the system is user friendly; proven rate of success; and the return on investment (ROI). Careful attention needs to be paid to calibration of fuel flow measurement systems applied to biomass-fired boilers. This is because biomass particles are more heterogeneous than coal and their flow fluctuates considerably more than coal. Hence, frequent and careful calibration is required in order to obtain an absolute fuel flow mass measurement. If not, only relative fuel flow measurements can be obtained. Moreover, for dense biomass flows (above 2.5 kg of biomass per second) some fuel mass flow measurement systems may not be accurate.

Having accurate fuel flow measurements, in all coal pipes, allows effective use of flow distribution devices. Recently, there has been considerable development in such systems. The most advanced ones are effective in rope breaking, have low pressure drop and a minimal effect on the primary air distribution, can be installed in different pipes/configurations and with different mills, and in most cases can be controlled automatically.

Other systems useful in fuel flow optimisation include instruments for measuring carbon-in-ash, oxygen and CO. These measurements can be challenging but if performed accurately, they are excellent indicators of fuel flow optimisation and can be used in the online control of both excess air and coal flow to the individual burners. Currently available, online, non-extractive carbon-in-ash analysers are much more accurate and less labour-intensive than extractive systems. Developments in oxygen and CO measurements enable simultaneous analysis of these emissions as well as other flue gas components. What is extremely important for all these systems is their sampling location as it determines the representativeness of the results. For example, oxygen and CO measurements should be performed in multiple locations by sensors deployed in a grid configuration.

The reviewed case studies make it evident that regardless of the chosen system and the scale of the optimisation, clear benefits of using flow optimisation equipment are reported by plant operators. Apart from advantages such as improved efficiency, lower NOx and CO emissions, reduced carbon in ash, lower overall operational cost and improved performance of various equipment (including particulate control technologies such as fabric filters and electrostatic precipitators), significant reductions in safety hazards (fires and explosions) and increased fuel flexibility are reported. However, despite being highly effective and commercially available, these systems are not yet seen in the majority of power plants.

2 Mills (pulverisers)

It has been reported that at least 75–80% of opportunities to improve the combustion performance at most pulverised coal-fired plants are dependent on a reduction in coal particle size (Storm, 2006). This is because the particle fineness has a direct impact on particle heating rates and the transportation of both oxygen and oxidation products within the particle (Dong, 2010). Consequently, reduced fineness contributes directly to increased NOx production and poorer boiler performance resulting in increased carbon-in-ash contents, slagging and fouling, secondary combustion at the superheater, elevated CO levels, higher particulate loading on emission control equipment, increased furnace exit gas temperature (FEGT) and increased spray water flows. Hence, both combustion and fuel flow optimisation should start with improving particle fineness and therefore mill performance.

Coal pulverisers are designed for a particular fuel grinding capacity or throughput at a specific Hardgrove Grindability Index (HGI), based on a defined raw feed coal size, its moisture content and a desired fineness level (Storm Technologies Inc, 2010). Hence, the pulveriser performance changes with changes in the fuel (Storm, 2009). Figure 1 shows that fineness and hardness have a greater effect on pulveriser performance than moisture content or coal feed size. Thus the common link for optimum coal combustion and pulveriser performance is fuel fineness. It is therefore important to tune the pulveriser correctly so it is delivering fuel of the required fineness.

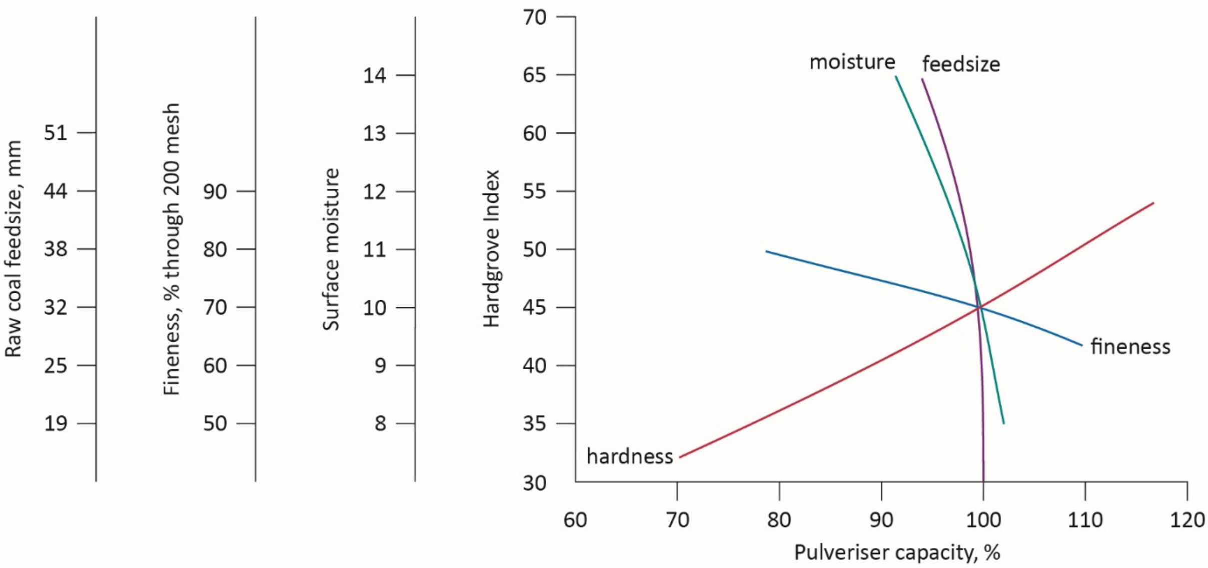

Figure 1 Pulveriser capacity changes with varying fuel properties and required fineness (Storm, 2008)

Although mill performance depends on many operating parameters and conditions and is limited by a number of factors including flame stability, milling capacity, pulveriser coal transport, duct erosion, tempering and fuel drying, there are several ways in which coal fineness can be optimised. Regardless of coal and mill type, these include control and/or improvement of the following: raw coal size and feed rate, mill elements, primary air flow (volume and velocity) and mill inlet and outlet temperatures. However, before optimisation can begin, the correct particle fineness and air/fuel flow measurements need to take place.

2.1 Particle fineness measurements and control

A typical requirement for coal fineness is 75% or more particles passing through a 200 unit mesh screen and less than 0.1% (for low NOx burners) remaining on a 50 unit mesh screen in each of the coal pipes (Storm, 2008). The finer the coal particles, the more the coal/air mixture resembles fluid flow rather than solids in suspension. This means better homogenisation of the mixture and consequently better distribution between burner lines. Coal fineness can be measured using traditional isokinetic or new online methods, which can be categorised based on the operational technique such as white light or laser. Some systems are listed in Table 1 and described briefly in the following sections. Most of these methods allow the simultaneous measurement of particle size as well as particle/air velocity and coal concentration. Regardless of a chosen technique it is important to sample all fuel lines of the pulveriser to ensure a representative sample is obtained.

Table 1 Examples of particle fineness measurement technologies

Technology	Example	Other measurements	Company
Acoustic emission	CFM System Coal Flow monitoring system	Coal flow, differences between roping and other changes	MISTRAS
Electrostatic	Electric Charge Transfer (ECT)	Mass flow, velocity, fineness	Foster Wheeler Energy Corporation
Laser	EUcoalsizer	Coal and air flow, coal mass flow, velocity and air/fuel ratio	EUtech Scientific Engineering
	Mecontrol PSA	Coal and air velocity and mass flow	PROMECON
Manual/isokinetic	Rotoprobe	Air/coal flow	Various
White light	MillMaster®	Coal velocity	Greenbank

2.1.1 Commercially available systems/equipment for online particle size measurement

Greenbank's MillMaster®

Developed primarily for pulverised fuel, Greenbank's MillMaster® can be used for analysing the particle size not only of different coals and biomass but also of other dry bulk materials such as cement.

The analyser uses a white light technology which, according to the manufacturer, is superior to conventional laser systems as it alleviates any potential laser hazards for equipment operators and eliminates the risk of spontaneous ignition during the analysis. Also, its accuracy is not affected by changes in particle velocity. After extracting particles from the air/coal flow the system conveys them to an interrogation chamber in the MillMaster® cabinet. The cluster of particles is backlit with the white light source and images are captured by a high-resolution monochromatic CCD camera. A short light pulse and a synchronisation device are used to 'freeze' the particle motion. An advanced edge detection algorithm is used to extract the particle shape information. The system counts and sizes the particles in each captured image and displays the size distribution in a way to suit the user. By default the particles are arranged into groups (<75, 75–150, 150–300 and >300 µm), maximum, minimum and mean particle sizes are also displayed (Greenbank, nd[b]). However, the system can measure particles in the size range 10–5000 µm (Lad, 2015).

PROMECON's MECONTROL PSA

MECONTROL PSA is a laser based particle size analysis sensor which is capable of both particle size and particle velocity measurements. It is usually combined with other PROMECON systems – MECONTROL Coal and McON air in order to offer more comprehensive mill performance assessment (primary air, coal mass flow, velocity and particle size). Measured particles are displayed as a percentage within the size groups (<62, 62–90, 90–125, 125–250, 250–355, 355–500, 500–710, >710 µm) (PROMECON, nd[a]).

Foster Wheeler's Electric Charge Transfer (ECT)

Foster Wheeler's Electric Charge Transfer (ECT) system is another online tool which can measure coal fineness. It uses the electrostatic method to measure particle size. In addition, the system calculates the mass flow of coal in each pipe while a computer-aided design and manufacturing (CADM) system calculates the mass flow of air at each burner. The data obtained are used together to establish the air bias needed to achieve balanced stoichiometric conditions at individual burners. Consequently, the bias at each burner is used by the plant's distributed control system (DCS) to automatically change damper settings so the correct air distribution can be achieved (Laux and others, 2002).

EUtech Scientific Engineering's EUcoalsizer™

This laser-based system provides inline and online, real-time analysis of coal particle size distribution, velocity and temperature inside a measurement volume that is placed at the tip of an insertable lance. A traversable lance allows a spatially resolved distribution along the cross-section of the coal pipe to be measured. In contrast to laser diffraction methods, the time-of-transition method covers large particles up to 4 mm diameter. Particles as small as 20 µm can be identified. Additionally, the system measures the flow velocity as well as temperature of the particles/gas mixture, which allows determination of coal and air mass flow in the pipe.

Systems software which is set up to analyse the data, display the status and store measurements provides information needed for real-time optimisation of coal fineness. Based on system readings, the coal fineness is controlled by adjusting the mill classifier. Consequently, the direct modification of coal fineness takes place (EUtech, Scientific Engineering GmbH, 2015).

Air Monitor's PfFLO III

Air Monitor's PfFLO III, which is described in greater detail as fuel flow measurement equipment (*see* Section 4.1.3), can also be used to determine coal fineness. The system, combined with real-time, continuous coal pipe air velocity, yields coal 'slip', which is defined as the difference between the coal particle velocity and the air velocity. Larger, heavier coal particles will have a much higher slip than small, fine coal particles. The PfLFO III continuously measures the coal particle velocity in each pipe and by adding a venturi (with a slight beta angle) to measure the air velocity in one pipe of each mill, can continuously measure the slip for this mill. This slip can be characterised to coal fineness via field calibration. Even without calibration, the slip can be used to compare the fineness from all mills in the plant. The mill with the highest slip will have the worst fineness and thus should be next in line for maintenance. This added feature of PfFLO III is a low cost indication of fineness (Earley, 2015).

2.2 Coal fineness optimisation

Once a reliable measurement has been performed the fuel fineness optimisation can begin. The most common practices used to improve coal fineness (and mill performance) include (Storm, 2008):

- ensuring the correct/optimal raw coal size and its supply to the mill;
- keeping the grinding elements in a good condition (no flat surfaces, 'perfectly round' rollers and tyres) and setting the correct grinding pressure, so even when fuel characteristics change (such as moisture, Hardgrove Grindability Index, feed size) the required fineness is achieved;
- 'keeping the distance and balancing the load' (in the vertical spindle mills) – the 'button' clearance between the spring canister and the journal assembly, so the correct pressure to the grinding elements is applied;
- setting the correct throat clearance and air flow (so rejects are minimised and adequate velocity of primary air is assured);
- maintaining the classifier, so overly coarse particles are returned to the grinding zone and adequate distribution of pulverised fuel to each mill outlet pipe is assured;
- maintaining suitable mill inlet and outlet temperatures so fuel drying and proper ignition at burners can be achieved.

2.2.1 Ensuring the correct/optimal raw coal size and its supply to the mill

Precise control of raw coal supply to the feeder is required not only to achieve the right particle fineness but for overall mill operation/capacity. Raw coal which is too fine can plug the pulveriser or delivery components upstream of the pulveriser. Large coal particles can plug throats and cause vibrations (Innovation Combustion Technologies, 2010). Additionally, when coal supply is interrupted coal stoppages above and below the feeder can occur. Without a supply of moist coal, the higher temperatures and air-to-fuel ratios present under the bowl migrate upwards into the grinding zone, where ignition can occur leading to mill fires and explosions.

Coal properties such as abrasiveness and grindability vary not only between different coal types but also within the same fuel and can affect mill capacity and performance. For example, the same fuel type can have different particle size and moisture content. These affect not only coal heating value, but its flow characteristics and density from a bunker to a mill and consequently from a mill to a boiler. Hence, the size of raw coal fed into the mill and the amount are important prerequisites before fuel pulverising. Generally, raw coal size should be consistently less than 19 mm (Dong, 2010) and it should be delivered to the pulveriser by a feeder which compensates for the variation in bulk density and feeds a fixed weight of coal in response to boiler fuel demand (Schenck Process Holding, 2015). It has been reported that gravimetric feeders have advantages over volumetric ones (Schenck Process Holding, 2015;

Greenbank, nd[c]). This is because the gravimetric feeders measure the actual mass of material going into a mill rather than interpolating through volume based system. In addition, gravimetric measurement allows auto adjustment to ensure the mass flow remains constant despite changes in coal density or voids in the coal loading (Lad, 2015).

2.2.2 Maintenance of grinding elements and setting the correct grinding pressure

Coal pulverisation is considered a high wear process. As the grinding elements wear, the grinding efficiency of the mill deteriorates. The type and rate of wear of grinding elements depend on the coal quality, the primary air volume and the pulverised coal and air velocity vectors above the bowl (table) (Birchett, 2013). Ensuring that all grinding elements of a mill are in good condition, properly aligned and preloaded, is paramount for optimum mill operation. Wear of mill components depends highly on compression and abrasion and to a lesser extent on impact. Compression wear is defined as an attrition process that acts normal to the surface, while abrasion is velocity driven and acts at a sharp angle shearing the surface (Birchett, 2013). Abrasion depends on the coal abrasivity, the pulverised coal/air velocity and velocity vector and the volume. Abrasivity varies with coal type. For example, low grade coals such as lignite are more aggressive and require higher throughput.

Vertical coal mills are more widely used. Within them, two primary zones can be distinguished: the grinding zone in the lower mill body and the classification zone in the upper mill body. The grinding zone consists of the grinding elements and the primary air entry for primary coal classification. The grinding elements contain the table (or bowl depending on mill design) and the tyre (or roll). Good condition of all of them is essential for optimum mill performance.

Mill design also influences wear of the grinding elements, more specifically, the orientation or position of the grinding elements relative to the throat vanes and the pulverised coal and primary air (PA) velocity vectors. The table (bowl) is usually located at or below the centreline of the primary air throat vanes; therefore the primary wear mechanism on the table is from compression and the sliding friction of the coal across the table. The orientation of the tyres is commonly above the centreline of the throat, thus apart from compression, the tyres are exposed to abrasion as they rotate in the mill. More abrasive coals have a greater impact on the tyres than on the table and it has been reported that in some applications the table to tyre wear life ratio is 2:1 or even 3:1. Therefore it is important to consider the design of the table and the tyre separately (Birchett, 2013).

Wear of mill components depends also on the properties of the material from which they are made. In recent years there have been many advances in these materials, namely ceramic composite materials (metal matrix composites), in which ceramic of specific properties is combined with a high chromium alloy. Such a composite material provides the extreme wear resistance of ceramic while maintaining the mechanical properties of the high chromium base metal, traditionally used in mills.

Setting the correct grinding pressure is necessary to achieve the required coal fineness, especially when fuel characteristics change. For example, in ball and race mills insufficient spring compression decreases capacity, fineness and can cause a grinding ring failure, while too high tension can lead to an increase in mill power consumption. Spring compression decreases as grinding elements wear; this decreases the force exerted on the top ring and necessitates periodic adjustment of spring balls. Accurate maintenance and inspection can help predict spring compression change based on hours of operation.

2.2.3 Throat clearance and pulveriser air flow

The right size of pulveriser throat clearance is important in order to minimise coal rejects. When the throat gap is oversized more than the optimum primary air flow is required to minimise rejects, as vertically flowing air has a low velocity. Apart from ensuring that the flow area of the pulveriser throat is set correctly, it is important for it to be compatible with the coal pipes and burner nozzle sizes so optimum furnace performance can be obtained. The optimum throat clearance can be determined by calculating the free annular jet area for the known desired air/fuel ratio (Storm, 2011).

Pulverised coal can be kept above the under-bowl pyrite area by mechanical means or by airflow. Mechanical means include increasing in the height of the 'bull ring' extension ring or the extension of flat surfaces above the rotating throat in order to trap or dam coal particles mechanically above the throat (Storm, 2011). Coal that falls through the throat opening will combust unless it is removed within minutes. The under bowl area is the most common location for fires in mills (Innovative Combustion Technologies, nd).

The air flow can keep coal particles suspended above the pyrite zone providing that the air is supplied with a sufficient velocity to prevent coal particles from settling. However too high an air flow to a pulveriser provides an abundant source of air for combustion of ignition sources such as smouldering coal in the classifier, pulveriser or raw coal under the bowl.

Once the throat clearance is verified, the correct pulverised air flow can be set. Primary air should typically be between 15% and 20% of the total airflow to achieve optimum combustion while maintaining a low NOx level (Innovative Combustion Technologies, 2007).

Optimum primary air flow depends on the type of pulveriser and should be ramped or rationed against fuel flow. Innovative Combustion Technologies (2007) reports that in most cases the optimum pulveriser air/fuel flow ratios are those shown in Table 2.

Table 2 Typical air/fuel ratios for different mill types (Innovative Combustion Technologies, 2007)

Mill type	Air/coal ratio
MPS and EL	1.5 to 1.8
Raymond Bowl	1.8 to 2.0
Ball tube	1.1 to 1.3
Attrita	1.2 to 1.6

It has been reported that the pulveriser throat velocity should be in the range of 33 to 38 m/s (when calculated on a free-jet basis). In order to maintain coal particles in suspension and eliminate coal dribble air at velocities above 35.6 m/s are required (Innovative Combustion Technologies, 2007)

2.2.4 Classifier maintenance

The classifier must perform two functions regardless of its type (static or dynamic):

- separate coarse from fine particles and recycle the former back to the mill for regrinding;
- balance the flow of coal to each burner line to the furnace.

Typically, the flow of coal particles through a classifier is several times the amount of coal flowing to the burners due to the large amount of coal recirculated within a pulveriser. Consequently, proper maintenance of the classifier is extremely important. Areas of a classifier where performance can be improved are illustrated in Figure 2. As reported by Storm (2009), there are a number of proven minor enhancements each of which can improve classifier performance. These include:

- surface smoothness of the classifier cone;
- synchronised classifier blade angles and lengths;
- inverted cone to classifier clearances;
- classifier outlet cylinder length and flared opening.

Additional improvements that should be considered when overhauling a classifier include:

- ensuring the surface smoothness in the upper turret section for good fuel spinning and uniform distribution (no surface discontinuities, such as 'pad eyes');
- ensuring the free movement and closure of the discharge doors (trickle valves);
- confirming the condition of the classifier cone assembly (no holes should be worn through);
- ensuring that the classifier blades are in the good mechanical order (Storm, 2009).

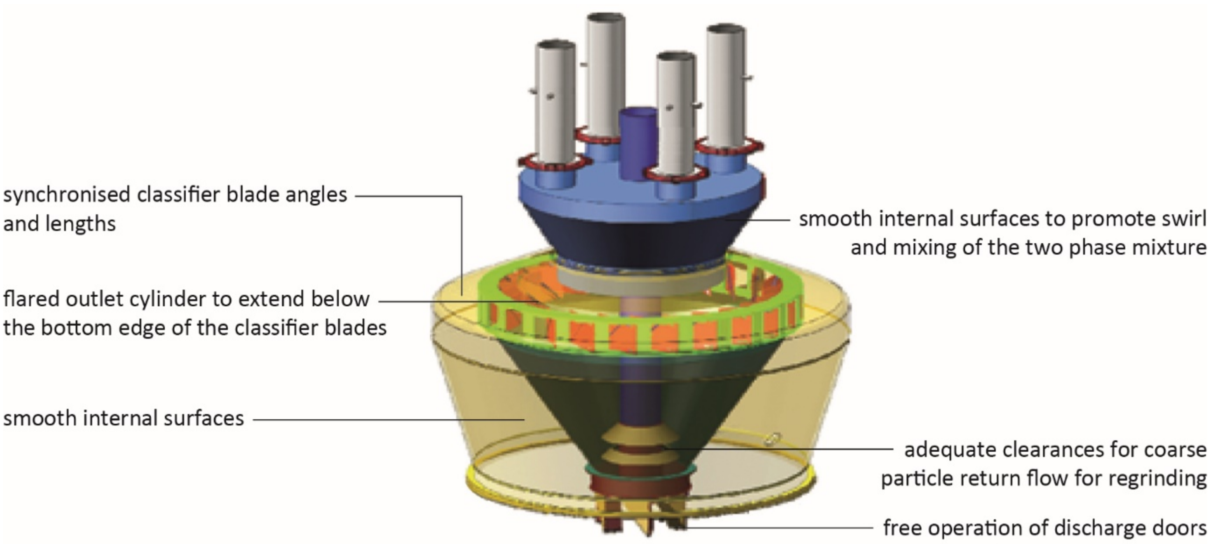

Figure 2 Areas of the classifier where performance can be improved (Storm, 2009)

2.2.5 Pulveriser inlet and outlet temperature/ combustion air temperature

The optimal mill outlet temperature must be maintained in order to ensure evaporation of coal moisture and proper ignition at the burners (Innovative Combustion Technologies, 2007). Mill/primary air temperature is controlled separately by adjustment of the mill's hot and cold air and should be as high as possible without exceeding the explosive limit (Dong, 2010) to facilitate fuel drying. Pulveriser inlet temperatures vary from around 160 to 370°C for low and high moisture coal respectively. Mill outlet temperatures vary from 54°C for low rank coals to 93°C for high rank coals. As primary air temperature affects coal drying, the correct secondary air temperature is key to rapid fuel ignition. Secondary air temperature is unit design specific and usually is around 316°C (Dong, 2010). For coals that are difficult to ignite (such as low volatile bituminous coals), the secondary air temperature can be increased by using a specially-designed air heater. For optimal combustion, both the mill exit and the secondary air temperature at the windbox should be monitored continuously. Primary air and secondary air temperatures can be regulated by adjusting the flow of 'cold' tempering air which is mixed with the flow of hot air from the air heater (Dong, 2010).

2.2.6 Typical modifications in pulverisers

If pulveriser performance is still less than desired after addressing mechanical and maintenance variables, pulveriser modifications are often needed to achieve the optimal particle fineness and fuel balance. There are various possible modifications. For example, in the B&W EL pulveriser (ball and race) common modifications include: extended classifier blades, angled classifier blades, extension of classifier outlet skirts, and installation of raw coal deflectors. Installation of extended classifier blades (which increases swirl resulting in rejecting coarser particles) on its own can improve coal fineness between 5% and 15% (Innovative Combustion Technologies, nd). Installation of angled classifier blades improves coal fineness by changing the diameter of the swirl, so the larger coal particles (which have higher momentum and are accelerated more than fines) collide with classifier blades and are rejected. Extension of classifier outlet skirts (by ~2.5 cm) changes the direction of coal particles in a downward direction towards the classifier reject area resulting in fewer large particles entering the fuel lines. Raw coal deflectors can prevent coal from passing from the inside to the outside diameter of the grinding ring.

2.3 Summary

It has been reported that at least 75–80% of opportunities to improve the combustion performance at most pulverised coal-fired plants are dependent on a reduction in coal particle size. Consequently, combustion and the fuel flow optimisation should start with improving particle fineness and mill performance. Before such optimisation takes place – accurate, reliable and real time measurements are necessary. Unfortunately, at the majority of power plants, particle fineness is checked only occasionally – once or twice a year. Furthermore, the dominant measurement method is manual isokinetic sampling. This is not only labour consuming but also has a large error and does not give simultaneous and real time results from all coal pipes. Hence, it cannot be used for the accurate, real-time optimisation of particle fineness and mill performance.

In recent years there has been considerable development in particle fineness measurement systems, which can be applied both to pulverised coal and biomass boilers. Based on a number of operational techniques, such as acoustic emission, electrostatic, laser and white light, most of these technologies allow the simultaneous measurement of particle fineness as well as particles and air velocities and fuel concentration. Most importantly, they provide reliable, real-time results. Consequently, the direct modification of coal fineness can take place. This is achieved by a number of ways, including: ensuring the correct/optimal raw coal size and its supply to the mill; keeping mill grinding elements in a good condition; applying the correct grinding pressure; setting the correct throat clearance and air flow; classifier maintenance and maintenance of suitable mill inlet and outlet temperature.

Regardless of a chosen technology, it is important to sample simultaneously all coal lines of all mills to ensure desired fuel fineness at all burners. Choosing the optimal sampling location and ensuring an appropriate calibration of the equipment is a must to obtain a representative sample.

3 Air flow measurement and control

All air flows in a power plant must be measured and controlled in order to achieve optimum combustion at the boiler and avoid problems such as high furnace exit gas temperature, secondary combustion, overheating in the back-pass as well as slagging. However, such air streams are turbulent and stratified, hot, moist and particle laden. This makes air flow measurement not an easy task. Additionally, air ducts to and from different mills have various geometries and lengths which impact air measurement devices, especially the most traditional ones (those used since the 1950s and 1960s), as most of them require sufficient straight and obstacle free pipe length to be installed. Furthermore, many also require field calibration. Most portable devices used to calibrate these systems require a laminar flow that does not exist in most combustion airflow ducts. Moreover, many devices provide air flow measurements based on an assumed cross sectional area of the given air duct. However, as air ducts expand and contract under hot and pressurised air streams, their cross section changes. Hence such measurements can have a considerable error. New, more advanced technologies for combustion air flow measurement attempt to deal with all these difficulties. Such systems range from advanced pitot tubes through electrostatic based systems to virtual and optical sensors. They are also more accurate than the old ones and designed to avoid clogging, corrosion and breaking. But all technologies have limitations and care should be taken to read product specifications for restrictions (temperature, flow, particulates, moisture, straight run and more).

Whilst there are many approaches to combustion air flow measurement, control and optimisation there are a few basic operational requirements. First, the primary air (PA) should account for 15–20%, and secondary air (SA) for 60–70% of the total air flow, with the remaining 15–20% being used as OFA. Secondly, PA should be balanced within ±3%, and SA to within ±5 to ±10% (Storm Technologies Inc, 2013). Thirdly, fuel balance between the lines should be ±10%. Before fuel is introduced, a clean air test should be conducted to balance the system resistance of each burner line leaving each mill, ideally to within ±2% of the mean (Storm 2009). Ideally, coal flow balancing should be based on dirty air flow measurement which is more representative of the actual flow conditions than the clean air test (Haumesser and others, 2002). However, the clean air test is considered a mandatory perquisite to fuel flow balancing (Storm, 2009).

When it comes to air flow measurement, the most commonly used, traditional procedure is based on differential pressure (dP). Differential pressure measurement of both primary air and mill air is conducted to avoid some typical coal pulveriser problems (such as insufficient coal drying, excessive duct wear, mill skids, explosions or fires inside the mill and ducts and insufficient fan power). An example of dP of mill versus dP of primary air plot is shown in Figure 3. It shows that for this power plant, the ratio of mill dP (vertical axis shown on the graph) to primary air dP (shown on horizontal axis) must be around 10:1 in order to avoid operational problems. If the ratio is too low there is a risk of explosions.

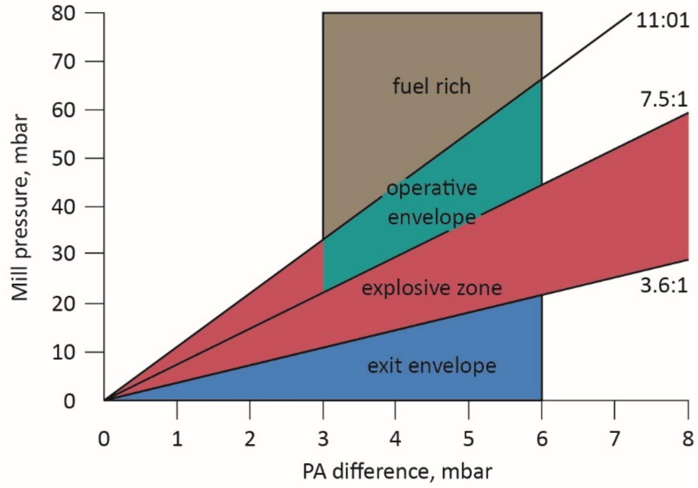

Figure 3 Example of operating envelope, relating mill dP to primary air dP

This type of measurement can be performed over different piping/profile elements and can be divided into: venturi, orifice, perforated plate or profile (carried out with the use of anubar, veribar or pitot tubes) measurements.

Most traditional flow measurements (those used since the 1950s and 1960s) have straight duct run requirements and/or require field calibration. Additionally, many of these devices are subject to maintenance problems (such as breaking of parts, pluggage of signal lines and build-up of debris). Many also require field calibration. Most portable devices used to calibrate these devices also require laminar flow that does not exist in most combustion airflow ducts. As such, many of the older technologies used in power plants are misapplied and do not yield accurate results.

3.1 Advanced air measurements

This section references more advanced technologies for combustion airflow measurement. These technologies attempt to deal with the difficulties of measuring turbulent and stratified flows that are particulate (ash) laden. But all technologies have limitations and care should be taken to read product specifications for limitations (temperature, flow, particulate, moisture, straight run and more).

3.1.1 PROMECON's MECONTROL family of air measurement systems

Based on the electrostatic cross-correlation principle, MECONTROL Air is a noteworthy example of a measurement system for primary and secondary air in pulverised fuel fired systems. The system consists of two sensors (antennas), which are aligned parallel to the longitudinal axis of the pipe.

As dust particles pass over system static sensors their electrical signals are read and correlated. The velocity can be determined from the time shift of the signals and the distance between the sensors. Using the cross-sectional area of the pipe, as well as the pressure and temperature of the stream, the volume and mass flow can be calculated. Each sensor pair provides an average velocity indication for flow over the length of the active portion of the sensor (antenna).

The length of the antennas, number of pairs and their locations are adjusted for each application, depending on the pipe/duct configuration. For low velocity and clean air situations, a signal booster 'range extender' is installed upstream of the pair of measuring antennas.

The system can operate up to 1100°C and measure velocities in the range 3 to 60 m/s (with the range extender). Typical accuracy of the measurement is ±2% and 0.1% repeatability.

Major advantages of the system include: it is independent of gas density; 100% linear measurement, which is not affected by K-factors and is not sensitive to the turbulent flows; drift and maintenance free; less straight duct distance needed for accurate measurements; no dust impact, no clogging as antennas/sensors have no openings; turndown ratio to 25.

The system is supplied with a central measurement cabinet base station which measures and collects data from up to 32 channels. The following capabilities can be provided: full SCADA (supervisory control and data acquisition) package, digital as well as analogue input/output, different connection possibilities (via modem, internet, ethernet), inputs available for external signals (for example, temperature, pressure) and large data storage capacities (Promecon, nd[b]).

McON air is a variation of MECONTROL air which is a single channel solution for air measurement. Another Promecon system – Multizone V Lance is designed to measure bulk air and flue gas in large ducts. It is capable of measuring flow in several zones along one axis perpendicular to the air stream.

3.1.2 Air Monitor Power's family of air flow measurement systems

Air Monitor Corporation have several airflow measurement systems which are designed to meet the challenging operating conditions of a typical power plant while providing mass flow measurement of PA, SA, and OFA within an accuracy of ±2–3% of actual airflow.

The VOLU-probe averaging pitot tube array compensates/corrects for much of the turbulence and stratification associated with the short duct runs of combustion airflow. Typically only 1–3 diameters are required for the VOLU-probe array (versus 8–20 diameters for traditional flow measurement devices). Where even more severe flow profiles exist (shorter duct lengths), a honeycomb air straightener is located upstream of the VOLU-probe array. This is all supplied in a short (~30.5 cm) section of duct and referred to as the CA Station (Combustion Air Station) (Earley, 2015).

Both of these measurement systems are also ideally suited to measurement of Primary Air; SA to an open windbox; SA entering each burner level of a partitioned windbox; SA being taken out of a windbox to supply multiple OFA ports ; at the ducted inlet of FD fans, and bulk SA entering each windbox of a corner fired unit.

Both systems operate on the Fechheimer-Pitot derivative of the multi-point, self-averaging Pitot principle to measure the total and static pressure components of airflow. It combines total pressure sensing ports with patented (US Patent No 4,559,835) chamfered entrances, and Fechheimer pairs of offset static pressure sensing ports to minimise the effect of directional airflow.

The systems use a high concentration of total and static pressure sensors positioned according to the log-Tchebycheff rule to sense the multiple and varying flow components that constitute the airstream's velocity profile. In order to minimise the positive error (measurements greater than actual) caused by the failure to account for slower velocities at the duct wall when using traditional equal area sensor locations the log-Tchebycheff's perimeter weighted sensor pattern is utilised. Depending on the duct shape there is a different spacing of total pressure sensors. For example, rectangular ducts need 25 or more points, maximum 15 cm or 20 cm apart, depending on duct size. Circular ducts need 12 to 30 points, along 2 or 3 diameters. Since the static pressure across the station is relatively uniform, a smaller number of static pressure sensors are used to minimise unrecovered pressure drop (Earley, 2015).

In order to provide high levels of measuring accuracy (3% of actual flow) under extreme conditions caused by turbulent, rotating, and multi-directional airflows normally present near fan inlets, discharge ducts, and directly downstream from duct elbows, transitions, the CA Station uses open, parallel cell, honeycomb panels to 'process' the air into straightened flow just prior to the total pressure measurement plane. The honeycomb panels sharply reduce the need for long, straight runs of a coal pipe before and after the station to obtain precise flow measurement.

While operating, the CA station produces minimum resistance to airflow, due to the unique honeycomb air straightener-equaliser section having a free area of 96.6% (Air Monitor Corporation, 2015).

3.1.3 EUtech Scientific Engineering GmbH's EUsoft air™

Virtual EUsoft air sensors are examples of air flow measurement technologies, which are capable of continuous determination of the complete air flows (PA, SA and OFA) from readily available DCS data. They belong to the latest generation of virtual sensors and as such, do not exist physically, but are sensors cast into software. EUsoft air technology is based on a physical model of the plant's hydraulic network, such as the pipes, manifolds, dampers and fans in their exact arrangement. It differs considerably from various 'numerically driven black-box approaches such as neural networks' (EUtech, 2015). This system requires little maintenance and its implementation is straightforward and does not need any on-site preparation.

The system is applied within a well-established framework in order to achieve the best possible results. The first step includes modelling of all air flow to one mill and consequent validation of the results. This is followed by modelling of the air flows in the remaining mills and their consequent implementation into the DCS system. Secondly, the hydraulic model is built from a comprehensive system elements library in accordance to a piping and instrumentation (P&I) scheme. Then, using historical plant data, the model is identified and verified. After this, the virtual sensor is integrated into the DCS.

The design of EUsoft air sensors is based on a powerful programmable controller. The virtual air measurements are transferred by default to the control system through a digital interface (such as Modbus TCP or PI server) for system inputs and an analogue interface for outputs. If required, the system can be equipped with analog ports.

So far, the system has been applied to coal power plants with a generating capacity from 100 MW to 1100 MW, where it successfully helped to identify and correct inadequately adjusted airflows (*see* Section 6.1.4 for a case study). Based on the system reading, existing faulty measurements installations can be identified and replaced (Pauquet and Turoni, 2015).

3.1.4 Optical sensors

Optical sensors for the measurement of air flow in coal fired power plants are an emerging technology, which have the advantage of being non-intrusive and less sensitive to environmental factors (Lockwood, 2015). Such sensors exploit the phenomenon of optical scintillation, in which light is reflected in by localised variations in temperature and density of the gas. The optical scintillation technique depends on advanced Digital Signal Processing (DSP) electronics to 'see' and measure the movement of turbulence found in the air flow stream. An example of such technology is the Optical Flow Sensor-2000C™ (OFS-2000C™) from Optical Scientific. The system is designed for continuous flow measurement of the primary and secondary air in large and small ducts as well as in stacks. It contains of an optical transmitter, an optical receiver and a control panel that are installed on the opposite sides of a duct, vent or other confined space. Additionally, it includes a resistance temperature detector (RTD) probe and built in self-test diagnostics. The measurement is drift free and provides an average velocity reading across the measured area. It also has the advantage of being independent of duct length, gas pressure, moisture and opacity and has no operational temperature limit (Optical Scientific, nd).

3.1.5 Thermal mass flow meters (TMFM)

Thermal mass flow meters can also measure air flow in large pipes and ducts. They provide direct measurement of mass flow rather than velocity and are based on the principle of convective heat transfer. While early thermal meters tended to be affected by fouling which alters the rate of heat dissipation, the newer designs avoid this by operating at the much higher temperatures of the surrounding air (Lockwood, 2015). As thermal flow meters have no moving parts they can be used in difficult applications including wet (saturated) gas and there is a reduced need for maintenance. They do not require temperature or pressure corrections and provide accurate and repeatable measurements over a wide range of flow rates (Steinberg, 2013). Examples of such meters include systems by Kurz Instrument Inc and Sage Metering Inc.

Kurz Instrument Inc offers a range of meters that can be applied in all air flow measurements in power plants including primary, secondary, tertiary and over fire air. For example, its inline mass meter – the Kurz 534FTB with its built-in inlet and outlet piping reducers/expanders is designed specifically for applications where flow disturbances caused by elbows, valves, and line size changes occur. The K-BAR 2000B multi-point insertion flow meter uses up to four sensors for measurement redundancy and is specifically designed for applications in large industrial stacks and ducts that commonly have wide-ranging velocity and temperature profiles. Another Kurz instrument – the Kurz 2445 is a portable meter which can be used in corrosive, high temperature conditions and measures both primary and secondary air. Depending on the model, the Kurz meters support process temperatures up to 260°C or up to 500°C (Kurz Instruments, 2015).

Sage Metering Inc offers a series of meters that are factory calibrated and configured for direct installation into the pipe or duct. Each meter consists of two sensors – resistance temperature detectors (RTD). One of the RTD is heated by the circuitry and serves as the flow sensor, while a second one acts as a reference sensor, and measures the gas temperature. The sensors consist of reference-grade precision matched platinum windings that are clad in a protective sheath for industrial environments. Sage offers insertion as well as inline TMFMs, with built-in flow conditioners that monitor the air and fuel flow rates to the burner. These direct mass flow meters are highly accurate (±0.5–1.0%) and repeatable (0.2%), even at very low flow rates (5 m/s) and have negligible pressure drop. The sensors' electronics can be either in direct or remote style.

3.1.6 Advanced pitot tubes and flow straitening devices

An example of the advance Pitot tube – The VAP3®/PA is offered by Eastern Instruments. The VAP3®/PA pitot places its 'high' port in line with the air flow and, according to the manufacturer, it prevents the tube from clogging and eliminates the need for a purging system installation in most cases.

The High Beta® Flow Conditioner, which integrates a set of flow-straightening vanes and an array of integral VAP3®/PA pitots within a spooled duct section, is a flow conditioning device. A converging duct section straightens the flow profile while accelerating the air passing through its round measurement area. As the High Beta® both straightens the air and profiles it prior to measurement, it can be mounted in areas where conventional differential pressure measurement devices cannot, such as directly downstream of an elbow, damper, or other obstruction. Air flow through elbows and dampers is typically accelerated and the converging duct section within the High Beta® accelerates the air further so that some or all of the pressure loss can be recovered. This minimises the required upstream and downstream straight duct requirements, increases the structural integrity of the duct and reduces the chance of duct expansion and contraction (Eastern Instruments, nd).

3.2 Combustion air control

Low-NOx burners require precise fuel and combustion air control in order to maintain a uniform and efficient combustion while reducing the formation of NOx. These requirements have been the main driver behind recent advancements in sensors and smart controls for utility boilers (Lockwood, 2015). Such technologies provide information on many combustion parameters and allow correlation between air/fuel flow, emissions and combustion efficiency. As seen in Figure 4, key combustion parameters (NOx, O_2, CO, LOI and boiler efficiency) vary depending on the air/fuel ratio. Hence, the optimum combustion within a boiler can be achieved only with careful control of fuel and air to the individual burners.

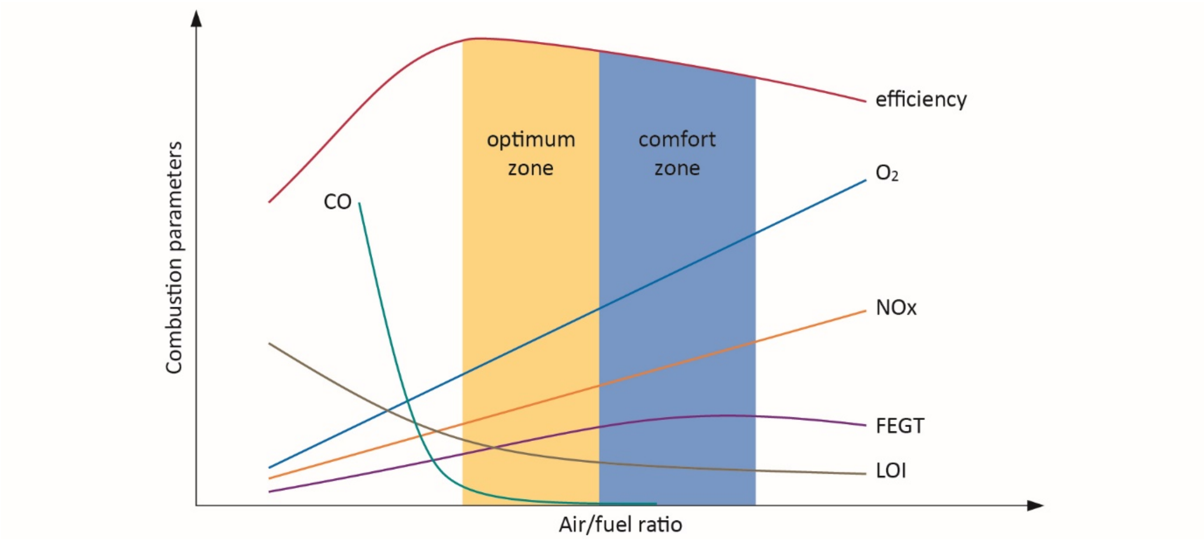

Figure 4 The variation of key combustion parameters with air/fuel ratio, showing the potential efficiency improvements achievable with optimised combustion (Widmer and Marquez, 2012)

3.2.1 Individual burner air flow measurement

Traditionally, coal power plants did not have any means to measure and control airflow to individual burners (Air Monitor Corporation, 2015). However, modern low-NOx burners are designed with a very strict fuel and air specification, and can only be operated to design by using correct air and fuel flows at optimum velocities. New low-NOx burners typically comprise inner and outer airflow barrels in order to introduce secondary air (SA) to the flame ball, adjustable swirl angled blades in each barrel and a combination of fixed and/or adjustable inlet sleeve/disk dampers. In the majority of cases the burners are equipped with actuators to facilitate DCS controlled variation of burner SA air flow depending on variations in fuel loads. An additional barrel for tertiary and quaternary air can also be incorporated into the burner. Hence, in order to ensure proper and even burner stoichiometry which leads to consistent flames in the furnace, all airflows in low-NOx burners must be controlled. Unfortunately, some low-NOx burners are equipped with no calibrated airflow sensing devices and most others lack any means to measure how much SA is entering the burner. This results in the need for extensive burner tuning so the emission targets can be met. As load conditions vary, the tuning needs to be constantly repeated. There are variations not only in fuel flow among individual burners but there are also significant burner-to burner imbalances in SA; therefor the only way to ensure balanced air distribution between different burners is to control airflow to each individual burner. It is not easy to access the secondary air inlets for maintenance or repair. This means any air flow measuring devices must be durable and repeatable and provide constant input signals to the DCS if a continuous combustion optimisation strategy (with continuous adjustment of the secondary airflows) is to be applied to each burner compartment (Air Monitor Corporation, 2015). Accurate and repeatable measurements of individual burner airflow require air flow probes to be positioned in the correct location and depth so that representative results can be obtained.

Air Monitor Power Individual Burner Airflow Measurement (IBAM™) is an example of an individual burner air flow measurement system, which has been applied to 'virtually every OEM and after-market burner design'. Each system is custom engineered to match the user's unique burner or OFA port and windbox configuration (Air Monitor Corporation, 2015). IBAM™ can be integrated into DCS burner control so burner-to-burner balance can be achieved dynamically over the varying fuel load.

IBAMs are based upon the Fechheimer-Pitot measurement principle, which measures the total and static pressure components of the air flow to calculate air velocity.

IBAM signals are directed out of the wind box to the Combustion Airflow Management System (CAMS) enclosure. There, the pressure signals plus airflow temperature are converted by the Combustion Airflow Management Module (CAMM) using a polynomial equation, into a density compensated mass flow output to the DCS. The CAMM also manages the AUTOpurge™ system which keeps the IBAM™ sensing ports and signal lines clear of accumulating fly ash. The purge cycle can be operated on a programmable interval or initiated via a dry contact from the DCS.

As reported by the manufacturer, IBAM™ is highly effective in flow control. For example, when used in conjunction with a CAMS, it provides relative burner-to-burner secondary air measurement within 5% accuracy and facilitates control of individual burner stoichiometry and air/fuel ratio, increasing the manageable range of burner turndown, among many other benefits (Air Monitor Corporation, 2015).

PROMECON's Individual Burner Flow Measurement (IBFM) like other PROMECON air measurement systems, the IBFM is based on the electrostatic correlation principle. It can be retrofitted to a variety of burners and work under different operating conditions (temperature range from 0°C to 400°C, velocity range from 8 to 80 m/s). The system can be easily integrated in secondary, tertiary and quaternary air barrels and there are no test runs on burner stand necessary.

IBFM provides vectorial measurement, which means it provides velocity measurement in the direction of the flow, and it can also be used to measure both axial and radial air velocity across each burner section. The system antennas are not affected by burner swirl angle, hence there is no risk of clogging and consequently no purging is required. The IBFM does not require calibration or maintenance and is drift free (PROMECON, 2015).

3.3 Summary

All combustion air streams in power plant should be measured in order to achieve optimal combustion at the boiler and avoid problems such as high furnace exit gas temperature, secondary combustion, overheating in the back-pass as well as slagging. However this is not an easy task. Combustion air streams in power plant are turbulent and stratified, hot, moist and particle and debris laden. Additionally, air ducts to and from different mills have various geometries and lengths which impact air measurement devices, especially the most traditional ones (those used since the 1950s and 1960s), as most of them require sufficient straight and obstacle free pipe length to be installed. Additionally, many also require field calibration. Most portable devices used to calibrate these systems require a laminar flow that does not exist in most combustion airflow ducts. Moreover, many devices provide air flow measurements based on an assumed cross sectional area of the given air duct. However, as air ducts expand and contract under hot and pressurised air streams, their cross section changes. Hence such measurements can have a considerable error.

More advanced technologies for combustion air flow measurement attempt to deal with the difficulties of measuring turbulent and stratified flows that are particle laden. These measurement systems range from advanced pitot tubes through electrostatic based systems to virtual and optical sensors. The new systems are more accurate than the old ones and designed to avoid clogging, corrosion and breaking. But all technologies have limitations and care should be taken to read product specifications for limitations (temperature, flow, particulate, moisture, straight run and more). Importantly, low NOx burners now have a choice of individual burner measurement systems. Also, the same air measurement devices can be used for both pulverised coal and biomass-fired boilers.

4 Fuel flow measurement and control systems

Conventionally, coal flow is monitored by the volumetric or, to a much lesser extent, gravimetric feed rate of coal to the mills and is directly dependent on the boiler firing rate and the current load demand of the plant (Lockwood, 2015). As power plants have multiple mills and fuel is transported to the individual burners via geometrically different pipes, it is 'natural' for fuel to take the easiest route (with the lowest pressure drop) to the burner (Greenbank, nd[a]). Unless some kind of fuel flow control devices are in place, uneven fuel distribution, roping and pipe blockages can and will occur. These result not only in inefficient combustion, high emission levels, and equipment erosion but can also lead to serious consequences such as fires and explosions. Hence, it is necessary to control and optimise fuel distribution from each mill to its corresponding burners. Such control and consequent optimisation are only possible when accurate, online and real time measurements take place. As pulverised fuel carried by air is a dynamic, two phase flow, traditional isokinetic sampling cannot provide immediate and accurate data necessary for timely combustion optimisation. Although there has been development in this type of measurement and some systems like INERCO's ABACO-PCSampler are semi-automated and offer more representative sample collection, power plants which need to be more flexible and environmentally responsible than ever, have to consider more advanced technologies.

In recent years there has been considerable development in fuel flow measurement and control technologies and currently there are a few systems commercially available. There is a number of factors which power plant operators need to take into account before choosing the most suitable instrument for fuel flow and control. These include: whether the equipment can be incorporated into the existing coal pipe geometry and if not what changes are required; need, the ease and time required for calibration, scale down and consequent shutting down of the plant; sensitivity of the system to high temperature and flue gas conditions such as stratification, moisture and different velocities; the operational mode of the equipment (stationary, mobile), if the system is user friendly and can be integrated into existing networks (DCS); the proven rate of success, and the return on investment (ROI).

Coal pipe layout is an important factor when it comes to choosing the most suitable technology. Some of the available instruments are suitable for horizontal pipes while others are appropriate for vertical pipe sections and their installation requirements vary considerably. For example, there can be a minimum length of straight pipe section and distance from bends and orifices required for the equipment to be installed. In addition, coal pipe acts as a waveguide for some equipment. This means that the pipe sections must be of sufficient length and where the installation takes place need to be smooth and plain without any obstacles such as flanges or other elements present (EPRI, 2006; Nabagło and Szczepanek, 2015).

Another important factor which must to be taken into account is the need for and ease of calibration, scaling and maintenance and the time required for these activities. Some systems are pre-calibrated in the factory while others need to be calibrated on site. These can be both time and labour consuming, and the shutting down of the mills/ power plant for a significant period may be required. It has been reported that for an absolute flow measurement some systems require a zero calibration and scaling, which can be complicated to perform especially when systems are used on horizontal coal pipe sections. Scaling also needs to be performed by means of comparison with another, more accurate system/method for coal flow measurement. Zero calibration may require mills to be stopped several times for many days (Nabagło and Szczepanek, 2015).

Additionally, in cases of biomass firing and cofiring with coal, careful attention needs to be paid to calibration of the system so the absolute flow measurement can be achieved. This is because most of the systems were initially developed for coal only and as biomass is more heterogeneous (particle size, shape, moisture content, density) than coal, its mass flow may have considerable deviations. Consequently, technologies applied for biomass and biomass/coal mass flow measurement may be able to provide good relative but not absolute measurement, unless more frequent and careful calibration is performed. Also, in cases of biomass firing, flows denser than 2.5 kg/s may oscillate more and may not be suitable for every fuel flow measurement technology.

In addition, systems which do not have automatic control dampers and splitters may not be able to use all the functions of the optimisation equipment. For instance, operators may be able to optimise the fuel flow but not control it (*see case study* Rybnik).

A report published by EPRI (2006) on five leading fuel flow control systems showed that flow conditions (and changes in these) such as temperature, velocity, moisture and coal stratification also impact instrument performance.

4.1 Commercially available coal flow measurement and control equipment

Due to the obvious limitations of traditional procedures, new digital techniques for flow measurement have been developed and introduced to the power market. Currently, there are several commercially-available instruments which are capable of online real time and drift free measurements. These systems can be either intrusive to some extent (have antennas inside the coal pipe) or non-intrusive such as a ring shape customised to the pipe diameter). In most cases these can measure velocity as well as fuel mass flow. There are considerable differences which the end users need to take into account such as need for calibration and required shut-down time of the mill/boiler, ease of installation, installation location requirements and compliance with appropriate health and safety regulations. Commercial examples of these technologies are listed in Table 3 and described in the following sections.

Table 3 Examples of coal flow measurement and control technologies			
Technology	**Example**	**Measurements**	**Company**
Acoustic emission	CFM System Coal Flow monitoring system	Coal flow, differences between roping and other changes	MISTRAS
Electrostatic	Electric Charge Transfer (ECT)	mass flow, velocity, fineness	Foster Wheeler Energy Corporation
	PFMaster	PF distribution , velocity and mass-flow rate	Greenbank
Laser	MECONTROL PSA	Coal velocity, particle size	PROMECON
	EUcoalsizer	Coal and air flow, particle size	EUtech Scientific Engineering
Microwave	EUCoalflow	Coal mass flow control	EUtech Scientific Engineering
	MECONTROL Coal/Pf-FLO III (in the USA)	Coal velocity, mass flow, coal concentration	PROMECON/ AMC
	MIC one	Relative coal flow in each pipe	MIC-USA
White light	MillMaster®	Coal velocity, particle size	Greenbank

4.1.1 GreenBank's PFMaster

The PFMaster® is a non-intrusive system which monitors both distribution and velocity of airborne pulverised fuel particles as they pass through its electrostatic sensors on their way to the burners. Its processor analyses signals and provides a relative distribution of PF for each bank or mill set of sensors, as well as the absolute velocity for each sensor sited within the PF pipelines. Sensors are customised to pipe diameter and have a circular shape. Each sensor consists of two non-intrusive detection rings which detect the magnitude of electrostatic energy, or charge, which is naturally present in airborne particles. These signals are then amplified and relayed to the PFMaster® processor for analysis. The system processor analyses the magnitude for each sensor and correlates the charge detected by each sensor ring. As the magnitude is proportional to the amount of electrostatic charge within the sensor, the time of correlation between two signals over a known distance allows the absolute velocity of particulates to be calculated. The relative fuel flow distribution across a given number, bank or mill set of sensors is calculated from the proportion of the total charge inherent in each sensor. When coupled with the total mass flow delivered to any bank of sensors such as a gravimetric feed input for a mill set of sensors, the system processor can convert relative distribution into an absolute mass flow over a given number of sensors. As sensor rings are set flush with the inside diameter of the sensor, there are no intrusive parts and sensors are protected from erosion and damage from mill pops or boiler flashbacks. As the manufacturer reports, when placed in a recommended position the sensor will provide a repeatable signal under normal working conditions at a full range of load conditions (Greenbank, nd[d]).

4.1.2 Mistras Products & Systems' Coal Flow Monitoring Systems (CFM)

Mistras Products & Systems' Coal Flow Monitoring System (CFM) is an example of an acoustic emission-based coal flow monitoring system. The CFM monitors changes in fuel flow and coal fineness as particles impact an elbow in the feeder tube, while the proprietary analyser evaluates the coal flow factor as it changes over time. The system analysers can detect, identify and differentiate between roping and other adverse changes. The system's sensors are non-invasive and provide real time monitoring of fuel flow in each pipe. The system can be integrated to DCS or stand-alone. When integrated into DCS, it shows trending of coal flow factor against other plant data and consequently permits long term monitoring of the effects of operating practices to develop long-term optimisation plans. A typical CFM system supports 16 integrated channels to cover four feeders from four mills. A dedicated base station can be added to provide alarms and trending analysis, as in the integrated system version (Mistras Group, 2009).

4.1.3 PROMECON's MECONTROL Coal (in USA licensed to Air Monitor Power as PF FLO III)

The MECONTROL Coal/Pf-FLO III system determines an absolute fuel mass flow by independently measuring the components of coal velocity and density. The coal density measurement uses a microwave based technology, while the cross-correlation method is used to determine the velocity of pulverised fuel.

The concentration of pulverised coal is measured by means of low power, low frequency microwaves, with each coal pipe functioning as its own unique wave guide. The measurement is carried out by two sensors aligned parallel to the longitudinal axis of the pipe, one functioning as a transmitter, and the other as a receiver. The sensors are positioned according to the pipe diameter, where the greater the diameter of the pipe the greater is the distance between the sensors. As coal flow may change with distance travelled, a third sensor is recommended in order to accurately measure the velocity of fuel, (Air Monitor Corporation, 2015). Reflector rods are installed upstream and downstream of the sensors to prevent reflected microwaves from returning to the measurement zone and consequently interfering with the measurement. The measurement sensors are connected to a transmitter board which performs all the processing needed to calculate the coal density, velocity, and mass flow as it provides all the outputs to the DCS via 4–20 mA signals, plus an ethernet connection to a PC, which is used for data acquisition, data historian, system commissioning, and configuration.

The system is suitable for installation in inclined, horizontal or vertical (except vertical down flow) pipes. For mill optimisation purposes, the manufacturer recommends installing the system in a vertical section of pipe, away from mill discharge, or in the first horizontal section of pipe within three to five diameters of the upstream elbow. For combustion optimisation, installation closer to the burners may be recommended. Other installation requirements include: no flanges in the measurement zone, fixed or variable orifices, the coal valves must be located downstream of the last reflector rod, and the pipe must not have a ceramic lining within the reflector rods. Test ports can be located anywhere except in the measurement zone between the two sensors.

The system operates in stand-alone mode and its measurements are independent of a central processor and/or external inputs such as mill feed rate. All in-pipe mounted components are constructed of abrasion resistant Tungsten Carbide.

Calibration of each transmitter can be performed with the use of a software utility such as Pf-PRO from a central PC or locally at each transmitter with a laptop computer and a direct cable connection or it can be monitored and configured remotely.

4.1.4 MIC's Coal Flow Analyser

MIC's Coal Flow Analyser is another system based on high current frequency microwave technology. It is capable of measuring flow from two to eight coal pipes associated with a given mill (as a portable unit) as well as monitoring all of the mills for a given boiler (as a permanently installed system) (Power & Industrial Services Corporation, 2015). It uses two sensors per coal pipe. The sensor tip is mounted flush with the inside of the coal pipe; therefore there is no intrusion into the coal flow. The sensors do not require any kind of wear protection. The sensor waveguide tube prevents pulverised coal from escaping from the sampling port and allows easy installation, maintenance and replacement of the sensor electronics, should this be required. The system determines the relative flow in each of the coal pipes and knowing the total mass of coal entering the pulveriser makes it easy to determine the mass flow in each coal pipe.

4.1.5 EUtech Scientific Engineering's EUcoalflow™

EUcoalflow is a microwave based system which continuously measures the coal mass flow and coal velocity inside pipes, as well as quantifying the coal flow imbalance from pipe to pipe. Consequently, the air/fuel ratio can be adjusted either by control of coal flow with adjustable orificing valves or by control of the secondary air dampers. The sensors are available in various designs, adapted to the specific operating requirements such as over-/low pressure, high/low temperature. The EUcoalflow can operate as a stationary and mobile system and can be seamlessly integrated into the DCS. As reported by the manufacturer, the EUcoalflow has a proven record of successful operation on over 1200 installations worldwide and is applicable to various solid fuels including hard coal, lignite and biomass.

When combined with other EUtech products, the system becomes part of the Total AFR™ Management system. The Total AFR Management is a turn-key, closed-loop control system that automatically adjusts the air/fuel ratio (AFR) using measurements of the air (EUsoft air) and coal particle size and coal flow (EUcoalflow and EUcoalsizer). The Total AFR Management system can be combined with EUcontrol, which is a real time combustion optimiser. Such a combination can determine the optimal settings of available variables including dampers, feeder speeds, overfire air and excess oxygen (EUtech Scientific Engineering GmbH, 2015; Pauquet and Turoni, 2015).

4.2 Fuel distribution devices

Older power plants were usually designed with one or two large pipes from each coal mill that split into smaller pipes using bifurcators or trifurcators, while the newest plants tend to have multi-outlet (4, 6 and 8) pipes. In both cases, balancing fuel flow in each pipe leg is stalled by differing pressure drops across the system/pipes. Additionally, the pressure drop in each pipe can be affected by changes in load, fuel type and particle fineness, wear and tear to the mill components, valves and piping system. As pressure drop is dynamic, it is necessary to install some kind of geometric device which can compensate for the differences in individual pipelines and subsequent changes/variation to pressure drops.

Traditionally, fixed geometry flow split improvement devices have been used to balance the pressure drop across the pipelines. These have mixed success for flow control and they quickly erode and/or reject pulverised fuel due to flat surface intrusion. Hence aerodynamic devices are a more effective solution. They can gradually increase the pressure drop in the pipeline as the damper blade is opened. These can be either adjusted manually or online (Miller and others, 2000). Reports of the effectiveness of this type of device are mixed, with the results likely governed by the initial cause of the flow imbalance.

There are a number of dynamic fuel balancing devices which are designed to control fuel distribution from each of the mill outlets and/or for the purpose of rope breaking. These can be controlled either manually or remotely by air actuators and positioners and frequently can be used in conjunction with an online PF flow monitoring system. Most manufactures offer customised products after creating computational fluid dynamic models for costumers' existing PF distribution data. Examples of these devices are described in the following sections.

4.2.1 Greenbank's family of PF distribution and control systems

Greenbank offers a selection of pulverised fuel distribution and control systems. For example, its CoalFlo Damper is designed specifically for PF flow balancing of multi-outlet mill/classifier arrangements. This device is customised for individual applications and is suitable for manual or actuated closed-loop operations. According to the manufacturer, the device addresses all the issues relevant to dynamic changes in PF pipelines, has a negligible pressure drop in open position and complies with PF code of practice. Having aerodynamic vanes, actuated on the spindle, the device allows fuel and air to flow smoothly whilst gradually increasing the pressure drop in the pipeline as the damper blade is opened. Consequently, the pressure drop in each classifier outlet is equalised without rejecting the fuel. Additionally, the internals are protected with wear protective linings while the blade is cast from an abrasion-resistant alloy (Greenbank, nd[e]).

Other systems from Greenbank include Variable Area Rope Breakers (VARB®) and Control Gates®. VARB PF diffusing systems are a family of non-intrusive rope breakers, which together with the control gates have been specifically designed to break the rope and then control, balance and trim the air/fuel ratio to the desired distribution down each pipe leg. The manufacturer offers different types of the VARB – each designed, on a line by line basis, for a different application. Use of CFD in each design ensures performances can be met before making actual plant changes (Lad, 2015). The device operates under differing air/fuel ratios and is unaffected by moisture or fuel type changes and is recommended to be used in a conjunction with the Control Gates, which are positioned immediately after the VARB® and designed to fine tune the fuel distribution.

The S-VARB® and the A-VARB® are recommended for vertical outlets. S-VARB® is the original VARB®, which works by gravity to reduce the velocity and induce spin. Thus the fuel particles become thoroughly mixed in the transport air before the pipe exit.

The A-VRAB® is designed to break particularly aggressive rope situations. It works in the same way as the S-VARB®, while having an incorporated throttle which agitates the rope before it is destroyed.

For plants which pulverise lignite using large Beater mills with square outlets the L-VARB® and T-VARB® are recommended. Square mill outlets have been shown to produce uneven, difficult to balance PF distribution. The T-VARB® has been specifically designed to address inverted splits found immediately after sharp elbows frequently present on t-fired boilers.

The H-VARB® is the second generation VARB®, developed originally to address the air/fuel ratio on horizontal bifurcations, trifurcations and multi-outlet splitters. It has been proven to work equally well in both horizontal and vertical modes, and in conjunction with the Control-Gate its performance is repeatable to within ±5% of the mean distribution under different fuel/air loadings (Greenbank, nd[c]).

4.2.2 Combustion Technologies NT Diffusing Coal Valve

Combustion Technologies offers a selection of NT diffusing coal valves, which have been designed for all pipe diameters and mill outlet types. The valves can be installed within the coal pipe, without removing a pipe section. All NT valve models have perforated (patent pending) damper blades – designed to dissipate coal ropes and can be operated manually or with an optional actuator.

The NT coal valves are available in several models. For example, the NTV Series can be installed in a location where fixed orifices are currently installed between Victaulic type couplings. The Riffle Replacement valve (NTR Series) is designed to be installed in the riffle housing, where it minimises pressure drop associated with the old riffle and allows precise control of the coal to the two outlet pipes. Another model – the Low Profile (NTF) series valve can be used in 'tight' piping locations where space is at a premium (Combustion Technologies Corporation, 2015).

The valve's effectiveness, especially in combination with the PfFLO III has been confirmed in numerous applications, examples of which are described in Section 6.1.1 (Case study – Crystal River Unit 4).

4.2.3 Leigh University's CoalCONTROL™ system

Developed at the Energy Research Centre (ERC), Lehigh University, the CoalCONTROL™ is an example of a coal flow balancing and control system for suction pulverisers, such as Raymond ball mill, with 2, 3 and 4-way splits. The technology is designed specifically to fit in existing riffle boxes. Although, applications of the system have been deployed for manual control, it has a proven record of reducing the fuel flow imbalances to less than ±10% in each coal pipe, for the range of pulveriser load, as well as improving burner stoichiometry. It is a low pressure device and its impact on the primary air distribution was found to be negligible in numerous field tests. The system installation payback time is well before 1 year and since 2004 it has been operating in over 50 coal-fired power stations. For example, the CoalCONTROL™ technology has been used to balance the fuel flow between a Foster Wheeler Double Ended ball mill and a 225 MWe front wall fired boiler (Bilirgen and Levy, 2005). In this case, four 3-way CoalCONTROL™ systems were designed, fabricated and installed in the place of existing 3-way coal distribution splits on two Foster Wheeler horizontal ball mills. Before the CoalCONTROL™ installation, the fuel flow imbalance was between +50% to -30% (deviation with respect to the mean between all pipes) which was reduced to ±5% after system application. Additional benefits included: a 1.27% increase in net electrical generation; a 5.58% decrease in NO_x emissions; a 12.43% decrease in average CO emissions as well as a 0.88% reduction in heating rate and a 4.56% decrease in LOI. The savings based on lower heat rate and reduced fly ash handling costs were estimated at $400, 000 per year, while return on investment was 5 months only.

In another installation, a 325 MWe coal-fired unit, the system was used to achieve a specified fuel distribution profile of 20/30/30/20% through each burner at each elevation. For this application, two CoalCONTROL™ 4-way riffles and flow controllers were designed and fabricated for one Foster Wheeler double ended ball mill. Before the system retrofit, the coal flow distribution was 25/25/25/25%. After the installation this was changed to 22/27/28/23% which is much closer to the required fuel distribution.

4.2.4 B&W PGG's EvenFlow™ system

EvenFlow™ is an example of coal flow optimisation system designed for pressurised vertical-spindle mills. It has been developed by the Energy Research Centre (ERC) at Lehigh University in collaboration with Babcock & Wilcox Power Generation Group Inc. (B&W PGG). The system consists of a number of flow control elements (FCEs), which are used to manipulate the coal flow to one or more mill outlet pipes. FCEs, which are installed in a mill outlet distribution turret, can be moved individually or in groups. Each FCE is individually situated and can be controlled with electric actuators or manually. There are several designs of the system. The exact version of EvenFlow™ used on a given installation depends on pulveriser size and number of outlet pipes (Fuller and others, 2011).

The first utility-scale demonstration of the system took place at Unit 3 of Lakeland Electric's McIntosh Generation Station in USA, where the system was used to balance the coal flow distribution (Fuller, 2014). The test involved placing the EvenFlow™ systems in B&W Roll Wheel 75G mill to balance the coal flow in eight coal pipes. The balancing strategy was carried in two steps – first by making adjustments to multiple FCEs, then by making fine adjustments to only one FCE until the coal flow distribution was nearly uniform. Before the system installation, the base line tests showed that the coal flow distribution between the eight mill outlet pipes varied considerably (deviation, with respect to the mean between all pipes, ranging from +55 to -20%). After the system installation, the coal flow between the pipes was balanced nearly entirely within a ±10% deadband. The system had negligible effects to the primary air flow and after 1 year from the installation no evidence of damage or any wear to FCEs was observed.

The system is commercially available. However B&W is working on its further development, which includes coupling the EvenFlow™ with an online feedback mechanism as well as developing a closed-loop, automatic optimization system (Fuller, 2014).

4.3 Summary

It is necessary to control and optimise fuel distribution from each mill to its corresponding burners to achieve optimal combustion. Such control and consequent optimisation are only possible when accurate, online and real time measurements take place. Traditional, manual isokinetic sampling is still dominant in the majority of power plants. This is despite the fact that this type of measurement is the least accurate of currently available systems. However, there has been considerable development in flow measurement and control equipment and there are currently a number of online technologies commercially available. These new, online fuel flow systems are based on a number of techniques including laser, white light, acoustic emission, microwave, electrostatic and mathematical cross-correlation. Their main advantages are accuracy and real time measurement. As with any type of technology, there are a number of factors which can affect their performance and power plant operators need to consider several factors before choosing the most suitable instrument for fuel flow and control. These include: whether the equipment can be incorporated into the existing coal pipe geometry, and if not, what changes are required; the need for, ease of and time required for calibration, scale down and consequent shutting down of the plant; sensitivity of the system to high temperature and flue gas conditions such as stratification, moisture and different velocities; the operational mode of the equipment (stationary, mobile), if the system is user friendly and can be integrated into existing networks (DCS); the proven rate of success, and the return on investment (ROI).

Careful attention needs to be paid to calibration of the fuel flow measurement systems applied to biomass-fired boilers. This is because biomass particles are more heterogeneous than coal and their flow fluctuates considerably more than coal. Hence, frequent and careful calibration is required in order to obtain an absolute fuel flow mass measurement. If not, only relative fuel flow measurements can be obtained. Moreover, for dense biomass flows (above 2.5 kg of biomass per second) some fuel mass flow measurement systems may not be accurate.

Having accurate fuel flow measurements, in all coal pipes, allows effective use of the flow distribution devices. Recently, there has been a considerable development in such systems. The most advanced systems are effective in rope breaking, have low pressure drop hence a minimal effect on the primary air distribution, can be installed in different pipes/configurations and with different mills, and in most cases can be controlled automatically.

5 Verification of fuel flow optimisation

Maintaining the air/fuel ratio in the narrow optimum combustion zone can be especially challenging for large multiburner low-NOx furnaces. As these boilers are subjected to frequent load changes, localised areas or transient periods of incomplete combustion can occur (Lockwood, 2015). Coal combustion in the boiler can be monitored and controlled via its reactants (coal and air flow measurement) or its products – flue gas and carbon-in-ash analyses. Flue gas analyses include CO, O_2, and NOx and furnace exit gas temperature monitoring. Additionally, analysis of the coal flame can also be used to monitor combustion. However, this report concentrates only on CO, O_2 and carbon-in-ash analyses and their usefulness in control and optimisation of air and fuel flow. These measurements are challenging, but if performed accurately, they are excellent indicators of fuel flow optimisation and can be used in online control of both excess air and coal flow to the individual burners (Yokogawa, nd). For a comprehensive review of the latest combustion optimisation technologies, the interested reader is referred to another IEA CCC report by Lockwood (2015).

5.1 CO and O_2 monitoring

Accurate monitoring of both CO and O_2 concentrations in the furnace is critical as it can be useful in determining excess air and hence control of air and fuel flow to the boiler. Due to the fact that the flue gas in the convective pass is relatively 'stratified' (as individual columns emitted by each burner) localised regions of high CO and O_2 can be present even in the economiser exit. Hence, it is of paramount importance to choose not only the most suitable system but also to have the sensors placed at multi-point representative locations so that accurate reading and consequent flow optimisation can take place.

Although, O_2 measurement is a useful tool in accessing excess oxygen and it is used to trim the excess oxygen set-point and adjust the air/fuel flow, it can be affected by air ingress to the boiler. Therefore, it should always be accompanied by CO monitoring, which is considered the most sensitive and accurate indicator of incomplete combustion (Lockwood, 2015).

There are a number of oxygen sensing technologies although electrochemical zirconia-based sensors are most commonly used in coal-fired burners. CO sensors can generally be divided into two types: infrared adsorption based and electronic ones which use catalytic combustion (Lockwood, 2015).

An example of a technology which measures both CO and O_2 with a grid of extractive probes is the Delta Measurement and Combustion Controls (DMCCO) system (Ferri and Volpicelli, 2015). The DMCCO system uses non-dispersive infrared (NDIR) and zirconia sensors for CO and O_2 measurements respectively. It also measures gas temperature as well as NO. Additionally the DMCCO is resistant to ash particles and can separate moisture and water vapour from the sampled gas. An example of its effectiveness, in combination with air and coal monitoring system, is described in one of this report's case studies (Crystal River Unit 4).

Other technologies which are capable of simultaneous measurement of CO, O_2 and other flue gas components (including NO, NO_2, SO_2) are based on tunable diode laser absorption spectroscopy (TDLAS). Commercial examples of such systems include ZoloBOSS from Zolo Technologies and TDLS200 TruePeak Analyser from Yokogawa (Yokogawa, 2010; Zolo Technologies, 2013). These systems position a source and a detector on opposing walls and create a laser grid which provides an average measurement of gas concentration as well as temperature over the entire measurement path. For more detailed information the interested reader is referred to an IEA CCC report by Lockwood (2015).

5.2 Carbon-in-ash measurement systems

Boilers which employ low NOx burners and those implementing over fire air at the top of the furnace in order to reduce emissions usually experience increases in carbon levels in the ash (Dong, 2010). Although it usually results from a combination of factors, research shows that the main reasons are incorrect air/fuel ratios at the burners and oversized coal particles. Hence, the ability to monitor carbon in ash accurately and in real time allows operators to identify and adjust poor mill settings and incorrect air/fuel ratios as well as burner settings. It also assists the plant operator to reduce the energy used in unnecessary heating of combustion air when the carbon levels are too low. Moreover, monitoring of carbon in ash is essential for ensuring fly ash suitability for use in different industrial sectors. The economic benefit of reducing carbon in ash can be considerable as it has been reported that reducing the carbon level by 1% can typically generate savings of 1 million US dollars per year for a large boiler (Greenbank, nd[f]).

A number of online carbon-in-ash analysers are commercially available. They can be broadly categorised into extractive and non-extractive systems, depending on whether the ash sample is extracted from the flue gas duct for analysis or not (Sorge and Larrimore, 1997). The extractive systems use intrusive sampling techniques, typically an isokinetic sampler to remove samples from the flue gas duct. In general, the extractive methods can be divided into two subcategories: direct and indirect systems. Direct measurement systems are based on an operating principle similar to that used in the standard loss on ignition (LOI) test. Indirect systems use different coal ash characteristics such as light reflection, light or microwave adsorption or changes in coal capacitance. In order to correlate UBC to the boiler performance the monitor used must have a total response time of less than or the same order of magnitude as the furnace. This is because boiler operating condition can change within a few minutes. It has been reported that the extractive systems are prone to problems such as blockage of the samplers and require installation of a cleaning/purging system. They also may have problems in obtaining representative results as they may be more sensitive to location/stratification of the dust flow around the sampling point than non-extractive methods. Although, many of the extractive systems are accurate, this report concentrates on non-extractive systems and those recently developed or improved. For more detailed descriptions of other commercial carbon-in-ash analysers the interested reader is referred to an IEA CCC report by Dong (2010).

5.2.1 Greenbank's G-CAM

Greenbank's G-CAM is based on the advanced microwave attenuation and phase-shift technology which analyses carbon in a sample collected by a patented compression system. As phase shift is closely related to the volume of analysed ash, carbon in ash measured in the precise volume of a compressed sample gives reliable measurements, unaffected by sizing, colour or chemistry of fly ash. The technology is designed specifically for large utility boilers which fire biomass or different coals. It offers an array of up to six flue gas extraction probes across the duct between the economiser and preheater, which allows the carbon-in-ash level to be profiled across the boiler. During the sampling process (6–10 minutes), the analyser maintains the temperature of the fly ash at well above the dew point, which maintains the fluidity of the sample and alleviates any material handling problems. The G-CAM® is a fully-automated system, which protects itself from contamination by purging air down the sampling pipeline at boiler start-up and low-loads. Additionally, it monitors the heating system and starts sampling when it is optimum. According to the manufacturer, the system is designed for 12 months maintenance-free operation and has an accuracy between ±0.5% and ±0.7%, depending on the carbon range (Greenbank, nd[e]).

5.2.2 PROMECON's MECONTROL UBC and MECONTROL UBC^{XT}

PROMECON's MECONTROL UBC and UBC^{XT} are noteworthy examples of non-extractive carbon-in-ash measurement systems. PROMECON's approach to measurement is unique as systems are installed directly in an electrostatic precipitator (ESP) ash hopper for *in situ* analysis. While the UBC system is based only on microwaves, the UBC^{XT} incorporates nucleonic measurement which provides laboratory level measurement analysis. The systems have a central measurement base station which controls all sensors and collates data. There is also the option of auto sampling that allows the operator to take the exact same sample that has just been measured by the PROMECON system to a designated bottle to be analysed for comparison and calibration purposes. Depending on the boiler operation, the system will need recalibration once or twice a year. Both PROMECON's systems can measure up to 20% carbon in ash with a reported accuracy of ±0.6% (UBC) and ±0.2% (UBC^{XT}). The UBC^{XT} version increases the accuracy of the measurement by adding a density measurement feature to the system. The density of the compacted fly ash in the measurement box installed on the bottom of the filtering equipment is measured by radiation with an additional sensor. This requires some safety measures to be taken (PROMECON, nd[c]).

5.2.3 ABB's Carbon-in-Ash monitor

ABB's Carbon-in-Ash monitor is another example of a non-extractive system based on microwave technology. It measures the carbon content of fly ash directly in the flue gas. The system utilises automatically aligned, parabolic mirrors located either side of the duct between the economiser and the air preheater which reflect microwaves of varying frequency back and forth through the flue gas. The amplitude at the resonant frequency is used to determine the carbon content per unit volume. A separate set of electrodynamic probes provides the total fly ash loading, from which the system calculates the carbon percentage by mass. Measurements take place every second with an accuracy of ±1%. The system can be integrated into a closed-loop optimisation control system (ABB, 2004).

5.3 Summary

Carbon-in-ash, oxygen and CO measurements are excellent indicators of fuel flow optimisation and can be used in online control of both excess air and coal flow to the individual burners. Currently available, online, non-extractive carbon-in-ash analysers are much more accurate and less labour intensive than extractive systems. Developments in oxygen and CO measurements also enable simultaneous analyses of these emissions as well as other flue gas components. What is extremely important for all these systems is their sampling location, which determines the representativeness of the results. For example, oxygen and CO measurements should be performed in multiple locations by sensors deployed in a grid configuration.

6 Case studies

This chapter describes case studies for coal and coal/biomass cofiring boilers. It shows that regardless of the chosen approach, equipment and the scale of optimisation, significant benefits can be gained from fuel flow measurement and control. It should be noted that the results depend highly on the pre-optimisation conditions and are case specific.

6.1 Coal fired power plants

6.1.1 Crystal River Unit 4

Crystal River Unit 4, located in Crystal River, Florida, is a 770 MW coal-fired power plant. This plant has a B&W opposed-fired boiler with 54 B&W DRB-4Z low NOx burners to which fuel is delivered by 6 MPS-89 mills, each with 9 coal outlets. Secondary air is transported to the burners via 6 compartmentalised windboxes (three at the front and three at the rear). Emission control equipment on this unit includes: SCR, cold side ESP and wet FGD. In order to balance air/fuel ratios at each burner, a continuous combustion management system (CCM system) was installed in 2010. The project consisted of integrating individual burner coal flow management, burner coal flow adjustment valves, secondary air management and actuation, CO measurement augmentation and O_2 measurement improvement. The CCM system for this project consisted of the following elements:

- installation of coal flow measurement systems on each of the burner pipes;
- the use of integral burner pitot tubes for measurement of secondary air flow;
- installation of linear pneumatic drivers on each burner to control secondary air flow;
- installation of automatic purge systems and primary air transmitters on existing primary air flow probes;
- installation of the coal diffusing valves on each pipe for coal balancing;
- relocation of O_2 measurement probes to a more representative location;
- installation of new CO monitors.

Air Monitor Corporation's (AMC) IBAM system was selected as the air flow measurement technology. In order to ensure accurate flow measurement, a full-scale model replica of the plant burners was constructed and tested at AMC's wind tunnel. The flow elements were characterised and equations were developed for use in the plant DCS. These equations consisted of three operating parameters (inner spin vane position, outer spin vane position and windbox pressure) and resulted in development of a coefficient which is multiplied by the differential pressure to produce a continuous final corrected flow rate. AMC's CAMS with automatic purge system was used to provide the probe dP to the DCS as well as keep the pitot tube free from ash.

AMC Power's Pf-FLO III coal flow measurement technology was selected for coal mass flow and velocity measurement. Burner line diffusing valves supplied by Combustion Technologies were installed in the burner pipes at the mills' turret discharge to improve fuel distribution. The valves are perforated butterfly style manually operated valves with truncated ends supplied by Combustion Technologies Corporation. Based on coal flow data, the valves were adjusted at the mill outlet. The use of the valves affects both the mass flow and velocity of the coal in the pipes. Thus the coal flow could be balanced to the extent possible within nine burner lines from each mill at the load range most generally used.

The air/fuel ratio control strategy was based on the idea that each burner can have a programmable set-point. With systems which evaluate the mass of secondary air and coal to each burner, secondary air can be adjusted when actual air/fuel ratio deviates from the set-point. This air is adjusted by the burners SA dampers. The coal flow balancing works as rough tuning and the secondary air flow is used to fine-tune the combustion air to the burner.

However, due to changes in load and total air, resulting from varying O_2 set-points, a fixed air/fuel ratio set-point was not practical. Instead, the air/fuel ratio set-point would change with changing O_2. The CCM logic analyses and sums the total air flow to the operating burners (ignoring out of service mills and their associated burners). This total shows the air/fuel ratio independently of the O_2 set-point. The average burner air/fuel ratio is then used as the target set-point by the DCS.

As the plant has compartmentalised windboxes encapsulating a single mill, the CCM air/fuel ratio is based on total airflow to each windbox compartment. The air is distributed to the burners within the compartment depending on the calculated target air/fuel ratio. The target air/fuel ratio is further continuously optimised for each compartment and accompanying burner row. Based on the PI Historian data, a dedicated CCM data ‘dashboard’ was developed that can be accessed remotely.

Another part of the project involved moving the original Yokagawa O_2 probes and cabinets. As the existing O_2 probe locations were very close to one wall of the duct they were not representative of overall flue gas. Multi-point test grids were set up to determine a better location, including the probe depth most representative of a true duct average 0_2 level. The pre-optimisation probe location was in a 12.2 m deep section of the boiler back pass downstream of the economiser. The new 2 m probes were located in a 4.6 m flue duct at the economiser hopper discharge. This resulted in a more consistent/representative reading for all eight probes due to the mixing effect associated with the hopper and the 90-degree turn as seen in Figure 5.

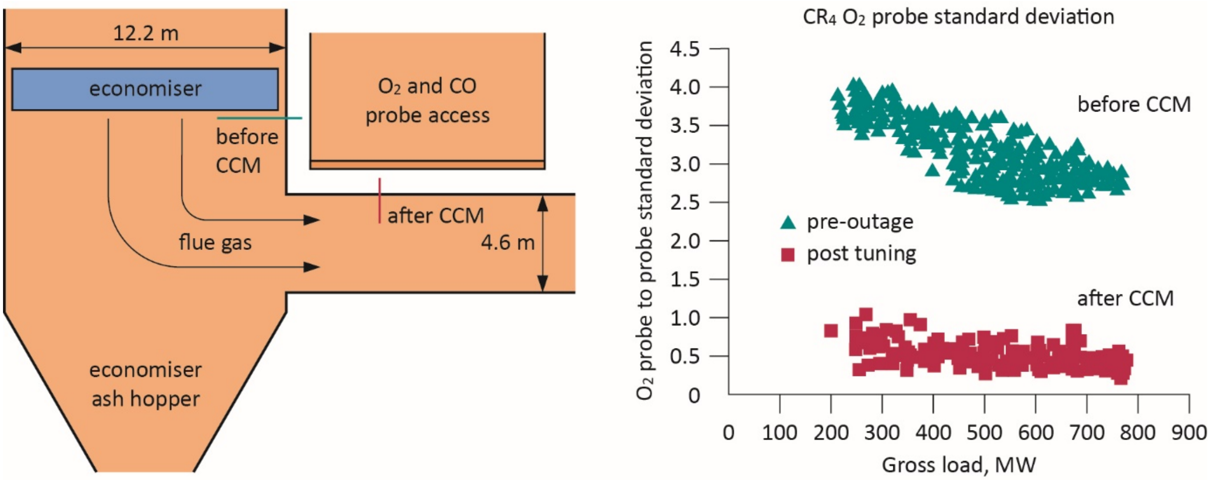

Figure 5 O_2 probe location and standard deviation before and after CCM (Estrada and Sisson, 2011)

Additionally, Delta Measurement carbon monoxide monitors were added to the unit at the same locations as the oxygen probes. This optimisation project had a clear benefit. First of all, balancing the air/fuel ratio alone resulted in a boiler efficiency gain of 0.25% points. Secondly, the new lower oxygen curve, which was installed due to the decrease in CO, yielded several benefits including reduced fan loading. Boiler NOx generation decreased by 25% at part load and 5–8% at full load, which resulted in savings in ammonia reagent and the SCR catalyst. A further 0.25% points boiler efficiency gain was achieved due to the reduced dry gas loss and reduced moisture in the air. This makes a total 0.5% points efficiency gain.

Furthermore, LOI levels became less erratic and decreased by approximately 1.5% points enabling the sale of ash on a more consistent basis. Additional unquantifiable benefits include improved ESP performance, reduced erosion due to lower flue gas velocities at full load and reduced risk of slag causing reducing atmospheres in the boiler (Estrada and Sisson, 2011). The cost of implementing the CCM project was approximately US$3 million providing fuel savings estimated at US$2.5 million/y (Earley, 2015).

6.1.2 Yeongheung power plant

Yeongheung coal fired power plant is on Yeongheung Island on the western coast of South Korea. It has a generating capacity of 5080 MW and in 2009 provided nearly 20% of the electricity supplied to the greater metropolitan area of Seoul (Park and others, nd). The plant was designed to fire bituminous and high-quality subbituminous coals with calorific values of around 6000 kcal/kg. However, in an attempt to lower operational costs, the power plant started to fire lower grade subbituminous coal of around 5400 kcal/kg. This resulted in the following problems: increased LOI and NOx and SOx emissions, increased pressure drop in the draught system, fan capacity shortage and frequent fan stalls, increased coal flow and consequently a need to operate all 6 mills per unit. Different remedial options were tried on different boilers. One option involved the use of the coal balancing system MECONTROL Coal from Promecon. This was applied to Unit 3 first. Like the other units of this power plant, Unit 3 has tight environmental standards (25 ppm for SOx, 15 ppm for NOx and 5 mg/Nm^3 for PM) and is equipped with SCR, ESP and FGD. It has a supercritical, tangential, coal-fired boiler from Doosan with a nominal capacity of 880 MW. The boiler convective pass is arranged in three main sections: an upper furnace (primary and secondary superheater sections and reheater second stage, an upper backpass (reheater first stage) and the lower backpass (economiser). There are six elevations of burners, with secondary air nozzles located below, between and above the coal nozzles. The secondary air nozzles located above the upper coal nozzle are typically referred to as close-coupled overfire air (CCOFA). Also, above the upper burner elevation two layers of separate overfire air ports (SOFA) supply additional combustion air. The system was designed such that only five out of six mills have to operate to achieve the desired load of approximately 303.3 t/h of bituminous coal. Each mill delivers coal to four nozzles at the four corners of the same boiler elevation. Primary air flow to the mill is controlled by both hot (from air preheater) and cold air (tempering) dampers. Each coal pipe has a different length and geometry, hence differences in fuel mass flows were anticipated. In order to minimise deviation between the four coal pipes, adjustable orifices have been installed on each pipe.

Optimisation of the fuel flow to the boiler started by installation of the mobile MECONTROL Coal system on four pipes of one mill. When the measurement and optimisation was completed the system was moved to next elevation/mill pipes. Velocity measurement showed that operational conditions where the maximum velocity was 29.1 m/s and minimum was 20.8 m/s, varied significantly from the manufacturer's design conditions (velocity of 24 m/s and deviation ±5%). The measured velocity was inversely proportional to the distance between the mill and burner. Velocity fluctuations were also observed, especially in the pipes with lower velocities, which contributed to partial coal accumulation in these pipes. Velocity deviations were minimised by adjusting orifices at mill outlets. As the primary air at the mill outlet is maintained by a control damper, the adjustment of an orifice at one corner could change inversely the velocity at the other corners. Hence, it was decided to reduce the opening of the adjustable orifice of the pipe with the highest flow velocity. This increased velocities at the remaining three pipes. The next step was to increase the orifice opening in order of velocity (starting with the lowest velocity). The whole procedure was repeated until the velocity at the four corners was balanced to ±5%. Effectiveness of the optimisation was confirmed by data before and after optimisation. For example, furnace temperature distribution showed that the average flame temperature increased by 46°C, while the maximum increase of 100°C was observed in the upper area of the furnace. This confirmed that the pulverised coal was delivered with equal velocity. Additionally, deviation in temperature at the four corners decreased considerably (between 179°C and 81°C) which resulted in partial settlement of fireball eccentricity and drift. Furthermore, overall steam temperature deviation between the left and right path (which is a known characteristic of a tangential boiler), decreased considerably except for the final SH (super heater) section (*see* Figure 6).

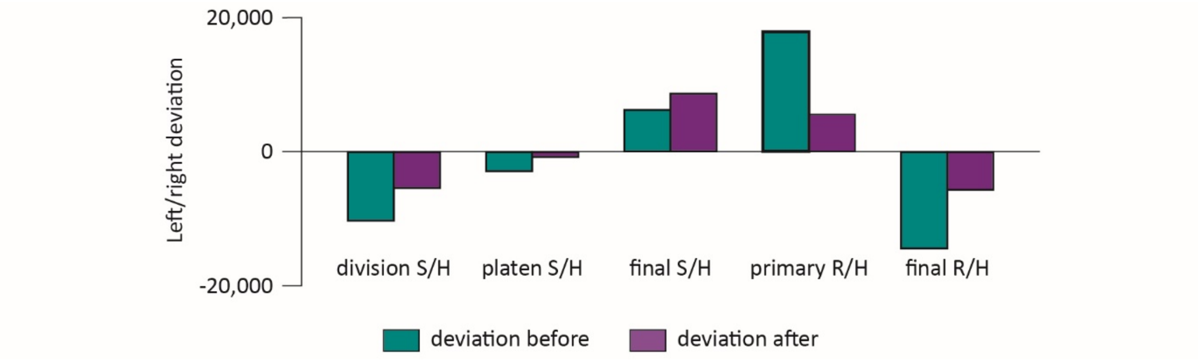

Figure 6 Steam left/right deviation before and after fuel flow adjustment (Park and others, nd)

An additional benefit was observed in CO emission levels, which before flow adjustment were always beyond the analyser measuring range (>495 ppm). After optimisation, emission levels were within the measurement range, which clearly indicates that the combustion efficiency improved. This was further confirmed by a 0.7% points decrease in the unburnt carbon in fly ash (UBC).

In general, SOx and NOx levels at the furnace exit increased as a result of the combustion temperature increase. However, due to the high efficiency of emissions reduction systems in place it had no effect on emissions released at the stack.

The estimated annual cost savings due to firing low grade fuel effectively were approximately US$1.5 million.

6.1.3 Chinese Control Group's Datong power plant

Datong Unit 7 is a coal-fired power plant with a total generating capacity of 600 MW. The plant fires bituminous coal in an opposed-fired boiler. The pulverised fuel is supplied by six vertical spindle mills, each with five outlets. In 2012, as part of a broader optimisation of the boiler, Greenbank's bespoke Coalflo balancing dampers with a coal flow measurement system PFMaster were installed. The Coalflo dampers were designed using computational fluid dynamics (CFD) analysis and took into account the plant parameters, so the shape and blade size were customised to ensure that pressure drops in the pulverised fuel lines could be adjusted and fuel flow balanced. After, the Coalflo dampers were installed on each pulverised coal outlet, each mill was set on steady conditions. A logical procedure was used to balance the fuel outlets from the mill. During the process, dampers on the legs with the higher coal masses were partially closed. The effects of the damper adjustments were monitored by PFMaster electrostatic sensors, which were installed on the vertical sections of pipework nearer to the boiler to allow real-time measurement of the relative mass and velocity. The effects of the changes were monitored by the system and further adjustments were then made as necessary to bring the mass flows in each pipe closer together. Some results are shown in Figure 7 and Figure 8. Figure 7 shows the effect of closing B3 and B4 valves, which had higher mass loadings. As seen from the graph, as the mass in legs B3 and B4 was reduced, the mass in leg B2 gradually increased. Also, the mass splits in legs B1, B3, B4 and B5 were brought together and the difference between B2 and B4 was reduced. Additional flow balancing is shown on C mill (Figure 8), where legs with the highest mass flows were again adjusted to balance the mass flows. Data were also taken into the station's DCS systems for further analysis.

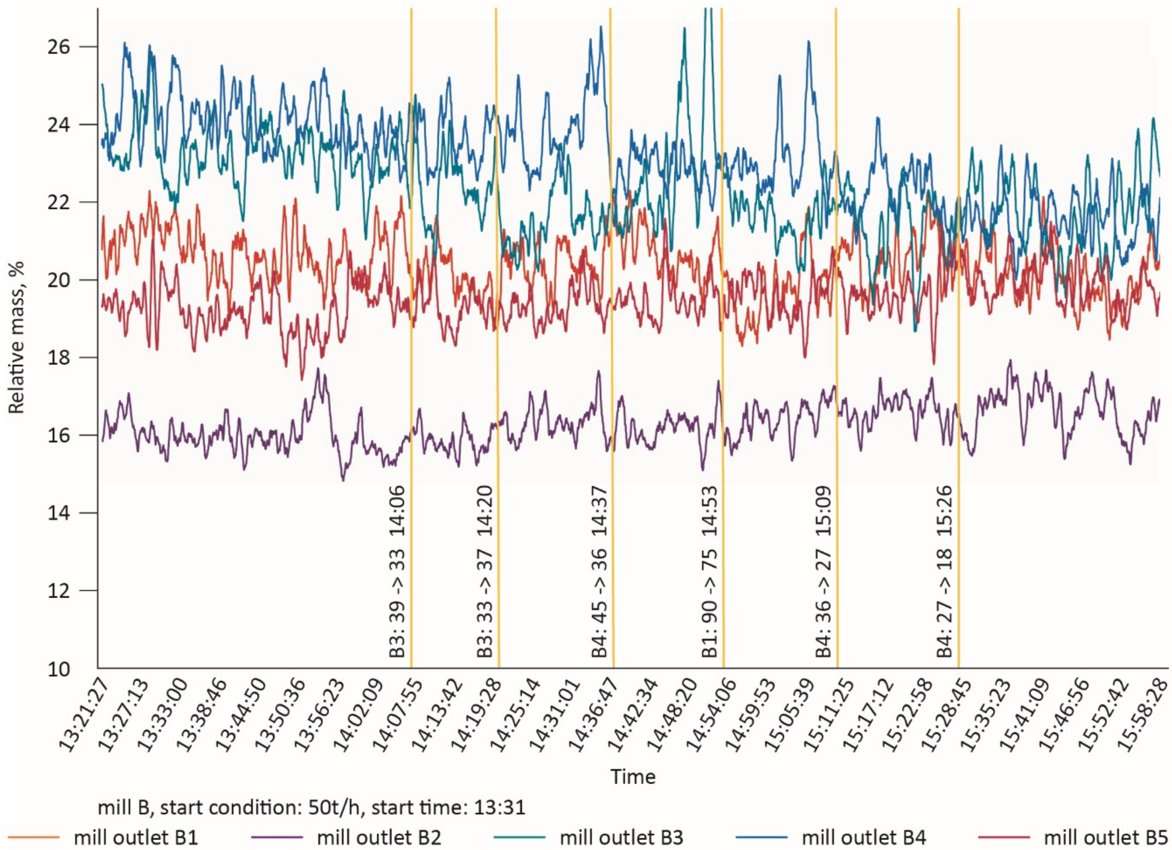

Figure 7 PFMaster showing fuel masses balancing (the effect of closing B3 and B4 valves, which had higher mass loadings) (Whitby, 2015)

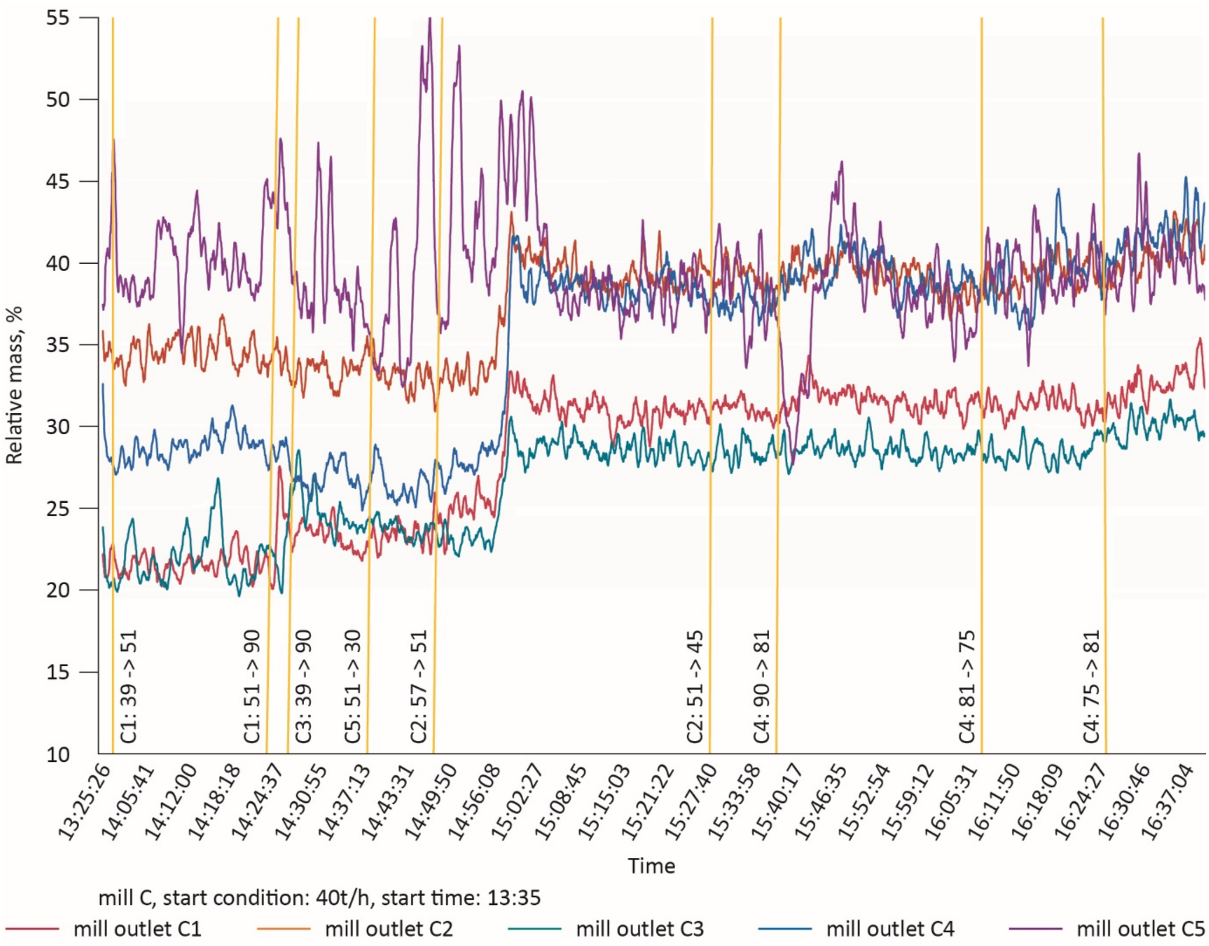

Figure 8 PFMaster showing further fuel flow balance (Whitby, 2015)

Upon evaluation, the Coalflo dampers used in conjunction with a PFMaster measurement system contributed to an improvement in boiler efficiency of 0.3–0.8% points and a reduction in NOx emissions of 16–25% (Whitby, 2015).

6.1.4 TPP Niederaussem

TPP Niederaussem located in Bergheim, Germany is a lignite-fired power plant with a generating capacity of 3669 MW and an average lignite utilisation of 25.38 Mt/y. The plant consists of four 300 MW units, two 700 MW units and one 1000 MW unit and on average generates 25.43 TWh of electricity per year.

In order to continuously optimise combustion conditions, RWE Power AG was looking for a technology to handle changing fuel compositions and operating parameters of one of their 700 MW tangential-fired boilers. The boiler has 24 burners and the fuel is supplied to them by 8 beater wheel mills.

As boiler operation is determined by dynamic behaviour and transient incidents such as load ramps, coal quality and component deterioration, true optimisation requires dynamic management and control of the manipulated variables. An EUcontrol boiler optimisation system was chosen and installed for this purpose.

As air flows are fundamental parameters used by the EUcontrol and the existing air sensors were not reliable or accurate, it was decided to replace them with EUsoft virtual air sensors. After modelling of air flow to all mills and consequent validation of the results, hydraulic model was built from a comprehensive system elements library in accordance to a piping and instrumentation (P&I) scheme. Then using historical plant data, the model was identified and verified. After this, the virtual sensors were integrated into DCS. The EUsoft air sensors were used to determine primary, secondary and overfire air for each mill.

Combining EUcontrol and EUsoft air led to significant improvements in overall combustion conditions. As seen in Figure 9, the excess oxygen was reduced by more than 10% in comparison with pre-optimisation conditions. Financial benefits resulted from controllable loss management strategies, including excess O_2 reduction, optimised air/fuel mixing, balancing of temperature as well as reducing superheat and reheat spray flows, controlling emissions of NO_x and CO and LOI, to name just a few. The total benefits were large enough to drive a return on investment (ROI) of 100% in the first year (Turoni, 2010; Pauquet and Turoni, 2015).

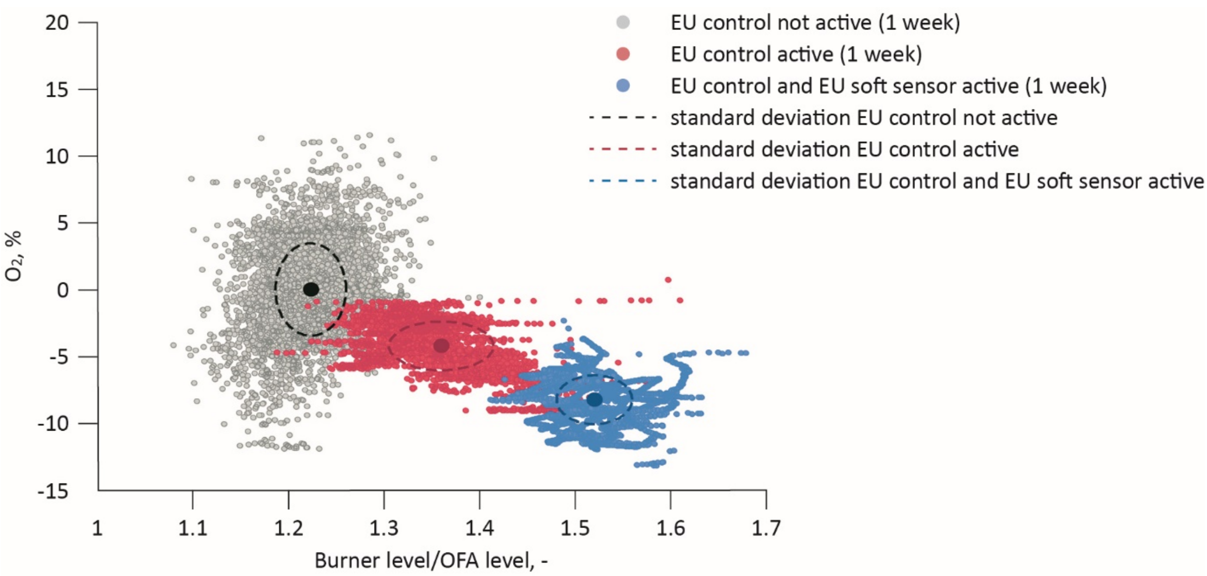

Figure 9 Comparison of excess oxygen levels for situation without and with EU control and EUsoft air sensors (Turoni, 2010)

6.2 Biomass cofiring power plants

6.2.1 EDF Poland – Rybnik power plant

Rybnik coal-fired power plant, which has a generation capacity of 1775 MW, is the largest plant in the Upper Silesia region of Poland. It generates over 9000 GWh/y of electricity, and supplies approximately 8% of the demand of the National Power System. It has eight boilers, which are supplied by 5–6 ball-ring mills. The mills have a maximum theoretical capacity of 33 t/h which in practice is equivalent to approximately 25 t/h, and are equipped with static classifiers with movable blades. The plant fires local hard coal with a maximum of 20–30% ash content and cofires up to 10% of biomass (agricultural) (Nabagło and Szczepanek, 2015).

Up-to-date fuel flow optimisation has been carried out in six of the eight boilers (one 'classic' and five low-NOx). This was performed using the MECONTROL Coal system supplied by PROMECON. As each mill has 4 outlet pipes, 6 portable cabinets (each with 4 channels) were needed. Due to the fact that this power plant does not have automatic coal dampers or splitters, it was decided to use the system for optimisation of each boiler/mill group at a time. Once satisfactory pulverised coal distribution was achieved, the manual flow dividers were set and the system was moved to another group of mills/boiler.

Depending on location constraints, different section lengths (~1.2–2.4 m) of pipes with ID of 0.46–0.51 m were chosen for the system installation. It was a general rule to install the sensors in vertical pipes at a location of three internal diameters (3 x ID) for the inlet and one internal diameter (1 x ID) for the outlet from bends and curves.

After installation, calibration–zeroing and scaling were performed in order to obtain absolute measurements. For the classic combustion installation, with front-wall burners in a symmetrical arrangement, pulverised fuel mass flow and velocities were analysed separately and PF was optimised to the same level in each coal pipe. For low-NOx boilers with front-wall burners and non-symmetrical vertical PF distribution (fuel and air staging), optimisation was performed in two steps. Firstly, PF mass flow and velocities were analysed for each mill separately to meet the requirements: 20–40% mass flow for upper burners (low concentration mixture), 60–80% mass flow for lower burners (high concentration mixture). Secondly, PF flow was analysed and consequently optimised to reach symmetry between left and right sides of the furnace. The results can be seen in Table 4.

It should be noted that up to 10% biomass was cofired for the low NOx burners.

Table 4 Examples of coal flow optimisation for a low-NOx boiler (Nabagło, 2015)

Boiler output (MWe)	Horizontal fuel flow distribution %			
	Before optimisation		After optimisation	
	Left side	Right side	Left side	Right side
135	44	56	51	49
190	47	53	51	49
225	40	60	50	50

Also, the flue gas temperature distribution profile was significantly improved, which is shown in Figure 10.

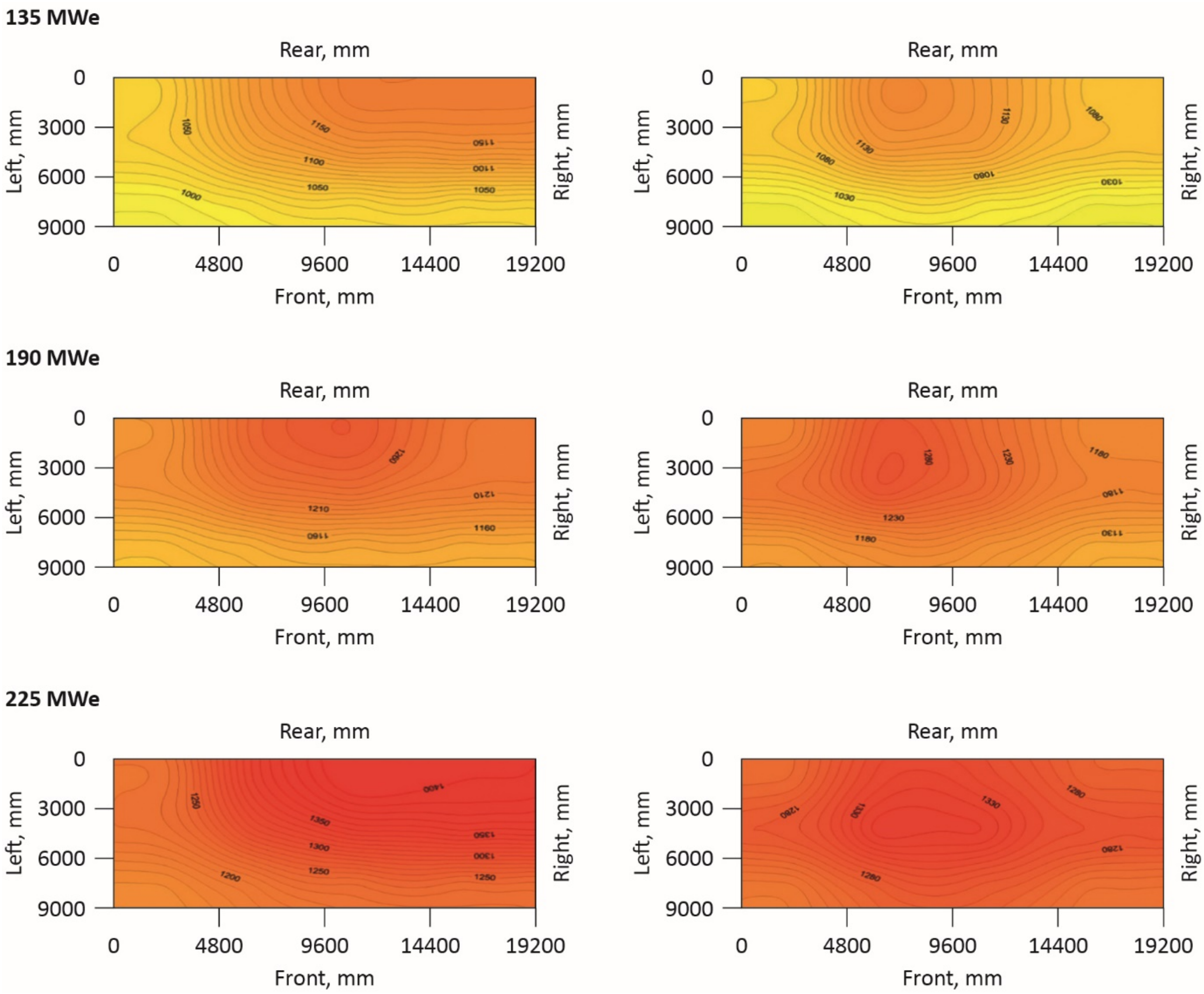

Figure 10 Example of furnace temperature profile before (left side) and after (right side) optimisation for a low-NOx boiler (Nabagło, 2015)

Additionally, the amount of unburnt carbon (LOI) in the bottom ash decreased by 2% points and in fly ash by 0.2% points. Other benefits included advanced diagnosis of: fuel duct deposition in the horizontal sections of coal pipes and flue gas return into some coal pipes during certain mill outages. Also, the fact that the system could be controlled remotely was an additional bonus.

During all optimisation procedures, including calibration, attention needed to be paid to the following:

- setting up the measurement curve correctly to achieve accurate density measurements;
- temperature in which the sensor was operating needed to be <120°C;
- electrical discharges which could affect data acquisition and power supply;
- temperatures to which signal cables were exposed should be <50°C (Nabagło and Szczepanek, 2015).

6.2.2 Gelderland power plant

The Gelderland coal/biomass power plant located in Nijmegen, Netherlands has a total generating capacity of 590 MW. Currently coal is the only fuel used. However, in order to reduce carbon emissions by 750 kt/y, the plant cofired up to 25% biomass between 2010 and 2012. During the trial, sawdust pellets were milled separately by three hammer mills and injected into coal pipes just prior to the inlets to the burners. Cofiring at 25% of biomass increased the plant biomass capacity from 44 MW to 180 MW.

The power plant has a low NOx opposed wall boiler with 36 burners arranged in three rows. However, biomass was only delivered to the bottom and middle row burners (24 in total). More specifically, biomass only was delivered to the middle row of 12 burners, whereas coal and biomass were delivered to the lower row of 12 burners. One hammer mill was connected to the bottom rows, while two hammer mills were connected to the middle rows. The coal was milled by six vertical spindle Babcock E-10 mills, each with two outlet pipes which are divided into three pipes, so one mill was able to deliver coal to six burners. Prior to biomass cofiring at 25% rate coal pipes had inside plates to allow better coal distribution to the burners. However, as the distribution was already fairly good and the addition of biomass leads to clogging of these plates they were removed. The biomass was fed to individual pipes by screw feeders. In order to determine the biomass flow and control the biomass dosing feeders, according to the heat demand of the plant, a PROMECON's MECONTROL Coal fuel measurement system was installed on the biomass lines (de Groot, 2015). Before the installation of 25% cofiring system, trials with a high density wood/air ratio, between 2–3.5 kg biomass in 1 kg of air were conducted in horizontal pipe sections, and later in vertical pipe sections. These initial tests showed that measurement in horizontal lines is rather problematic, especially for high density flows due to stratification of the fuel flow. Therefore vertical pipeline sections were introduced by making large U-bends in the existing horizontal lines.

Figure 11 shows example velocity measurements from an 8% cofiring test trial during which one hammer mill delivered biomass to the bottom and middle burner rows. For this test three velocity measurements were performed with sensors positioned at 0°, 120° and 240° around the circumference of the pipe. Typically, measurements are only taken at one location. However, in this case three sensor locations were chosen to determine if roping was occurring and what impact it might have on the measurement results. During measurements, there was constant air flow, supplied by a roots blower. The amount of biomass was varied between 20% and 40% and finally to 60% load. Increasing the mass flow of biomass, increased the biomass/air mass flow ratio up to about 3.5. As seen in the graph, increasing biomass/air ratio increased the fuel flow oscillations. The three velocity measurements were consistent with each other. Additionally, as predicted, the air velocity decreased with increased biomass loading. This was due to several factors including: increasing fuel increases the discharge pressure of the blower (more transport), internal leakages in blower, and less air being available for fuel transporting.

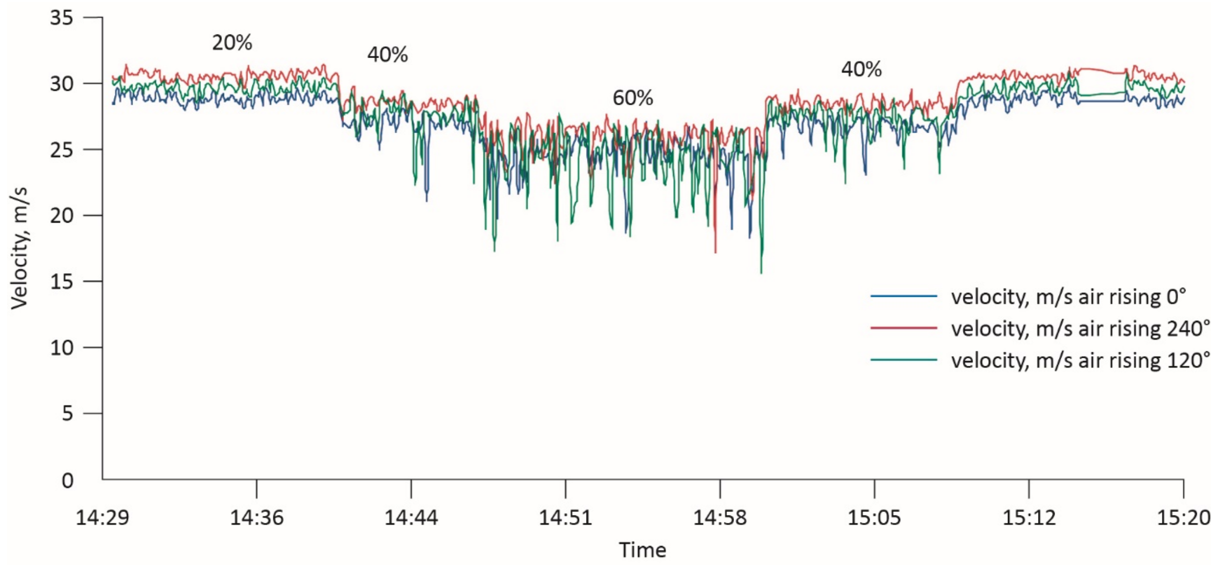

Figure 11 Biomass flow (velocities) pulsations (D'Hubert, 2015)

All the measurements were relative as absolute measurement of biomass would require frequent system calibration due to variations in biomass properties. This is contrary to the absolute measurement of coal flow, for which PROMECON's system comes with an initial calibration. In this case relative measurement was sufficient for the flow optimisation as it showed trends in fuel flow with variation of fuel concentration and velocities, which allowed optimisation of fuel dosing to the individual burners, thus improving combustion in the boiler.

The tests provided better understanding of the biomass flow behaviour and helped in the design of future biomass transport pipes as well as optimising biomass/air ratios and velocities.

6.3 Summary

The reviewed case studies make evident that regardless of the chosen system and the scale of the optimisation, plant operators report clear benefits of using flow optimisation equipment. Although the results depend highly on the pre-optimisation conditions and are case specific, they all achieved common gains. These include: improved efficiency, greater flexibility, lower NOx and CO emissions, reduced carbon-in-ash, lower overall operational cost and improved performance of various equipment such as PM control technologies, significant reductions in safety hazards and increased fuel flexibility.

Despite being highly effective and commercially available, these systems are not yet seen in the majority of power plants. However, this is starting to change as today's power plants need to be flexible and meet ever more stringent emissions limits while remaining economically viable.

7 Conclusions

The fundamental improvement in combustion efficiency that air and coal flow balancing can achieve in pulverised coal and biomass-fired boilers, is frequently overlooked. As a result, opportunities to reduce emissions, carbon-in-ash, maintenance and operating costs and to eliminate safety hazards, while increasing fuel flexibility and generating saving/profits are also missed (Estrada and Sisson, 2011).

Optimum combustion within a boiler can only be achieved with careful control of fuel and air streams to the individual burners (EPRI, 2006). Accurate, repeatable and near real time measurements of pulverised fuel fineness, mass flow rate, and all combustion air streams are indispensable perquisites to fuel flow control and optimisation. Although such measurements are challenging, there are a number of reliable and proven technologies commercially available.

The majority of opportunities to enhance combustion performance by improving the performance of coal mills depend on reductions in coal particle size. Hence, fuel flow optimisation starts with work on fuel fineness/mill performance. Measurement of coal fineness is a useful diagnostic tool which can provide immediate performance improvement by adjusting mill settings. There are a number of new, non-extractive online particle fineness measurement systems. These are accurate and less labour intensive and above all can provide real time results in contrast to traditional systems based on manual isokinetic measurements. In most cases they can also determine additional parameters such as coal velocity or coal mass flow. Once the fineness is measured, the mills can be optimised. This includes adjusting various parts of the mill such as throat clearance, spring compression, alignment of classifier blades as well as supplying an adequate amount of primary air at the right velocity and maintaining the optimum mill temperature.

All air flows in a power plant must be measured and controlled in order to achieve optimum combustion at the boiler and avoid problems such as high furnace exit gas temperature, secondary combustion, overheating in the back-pass as well as slagging. Considerable progress has been made on measurement and control of all combustion air streams. New systems range from advanced pitot tubes through electrostatic based systems to virtual and optical sensors. Additionally, low NOx burners now have the option of individual burner measurement systems.

Particle fineness measurement is dominated by traditional isokinetic sampling in the majority of power plants, despite the fact that this type of measurement is the least accurate of currently available systems. New, online fuel flow systems are based on a number of techniques including laser, white light, acoustic emission, microwave, electrostatic and mathematical cross-correlation. As with any type of technology, there are a number of factors which can affect their performance such as instrument location, proximity to an orifice, flue gas temperature and velocity. Consequently, power plant operators need to consider several factors before choosing the most suitable instrument for fuel flow and control. These include: whether the equipment can be incorporated into the existing coal pipe geometry, and if not, what changes are required. Additionally, careful attention needs to be paid to calibration of the fuel flow measurement systems applied to biomass-fired boilers. This is because biomass particles are more heterogeneous than coal and their flow fluctuates considerably more than coal. Hence, frequent and careful calibration is required in order to obtain an absolute fuel flow mass measurement. If not, only relative fuel flow measurements can be obtained. Moreover, for dense biomass flows (above 2.5 kg of biomass per second) some fuel mass flow measurement systems may not be accurate.

Instruments for carbon-in-ash, oxygen and CO measurements have been developed further. These measurements are excellent indicators of fuel flow optimisation and can be used in online control of both excess air and coal flow to the individual burners. Currently available, online, non-extractive carbon-in-ash analysers are much more accurate and less labour intensive than extractive systems. Developments in oxygen and CO measurements enable simultaneous analyses of these emissions as well as other flue gas components. What is extremely important for all these systems is their sampling location, which determines the representativeness of the results. For example, oxygen and CO measurements should be performed in multiple locations by sensors deployed in a grid configuration.

The reviewed case studies make evident that, regardless of the chosen system and the scale of the optimisation, plant operators report clear benefits of using flow optimisation equipment. Apart from advantages such as improved efficiency, greater flexibility, lower NOx and CO emissions, reduced carbon-in-ash, lower overall operational cost and improved performance of various equipment such as PM control technologies, significant reductions in safety hazards and increased fuel flexibility are reported. Despite being highly effective and commercially available, these systems are not yet seen in the majority of power plants. However, this is starting to change as today's power plants need to be flexible and meet ever more stringent emissions limits while remaining economically viable.

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