Power-Gen 2008, Orlando, USA

Online measurement of coal fineness and air-fuel ratio inside the coal pipe

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Introduction

Knowledge of the coal particle size distribution, coal mass flow and the air/fuel ratio inside the pipe is a pre-requisite for optimal combustion and boiler performance. Since combustion takes place at the microscopic particle scales, the fineness has a strong impact on the ignition delay, the adiabatic combustion temperature and the combustion time. These combustion parameters in turn determine the carbon-in-ash level or loss of ignition (LoI), the NO_x and CO emissions, the temperature profile and the heat transfer properties in the furnace as well as the propensity for slagging. Contributing to the problem, the particle-size spectrum is not a constant but may undergo rapid changes. Not only does the fineness vary with the type of coal (including water content) but also with the mill set-up and operating conditions and its wear and tear – the advent of fuel switching strategies complicating matters even further.

To tackle these problems, a laser based system – EUcoalsizer - was designed and built. It is based on a time of transition technique to measure the particle size distribution, velocity distribution, particle density and temperature inside a measurement volume positioned at the tip of a lance. The system measures particles in the range from 20 µm up to 4 mm and velocities up to 160 ft/s. By traversing the lance through the pipe, spatially resolved measurements along the cross section of the coal pipe are collected and analysed *online*. This permits direct correlations and feedback control between the mill settings (hopper load, mill speed and classifier setting) and the boiler behaviour which would not be possible when using conventional sieving due to the time lag between sampling and analysis. With the help of the measured velocity distribution not only the mass flow of the coal can be calculated but also the mass flow of the gas (air) flow since the smallest particles have a very high level of entrainment and follow the transporting gas with little slip. *Thus, the air-fuel ratio can be directly determined.*

EUcoalsizer is directly applied to the coal pipe *via* an adapter. The complete system consists of a portable control unit containing the electronics and pneumatics (20” x 8” x 15”) and the lance (diameter 2”). Much emphasis was placed on robustness and easy handling. Additional analytical functionality (e.g. online RRSB plots) contributes to the system´s acceptance. A series of test measurements was done in different power plants and with different coal types to validate reliability and reproducibility. The results show a very good match with conventional sieving analysis. Compared to the standard sampling techniques, EUcoalsizer cuts down the required time to 20 %, not counting the time to analyse the probe. In some cases, in particular where advanced low-NO_x combustion systems were installed, significant efficiency improvements could be obtained.

The status quo of fineness measurements

Each coal has its distinctive grinding and sampling characteristics, and these change with production conditions. Even when standard sampling methods are employed, differences in sampling results can occur among analyses taken. These differences may stem from the inherent variability in coal properties and from the fact that measurements of a variable substance are only estimates of average values. To approach a “true” value it is necessary to have a series of analyses on the same coal to observe the variability in inherent properties and in sampling itself.

The direct cost of coal grinding is a function of the wear and tear of the powdered coal mill , which in turn is influenced by the expected particle size spectrum of the coal dust and thus of the mill settings, e.g. hopper load, mill speed and separator adjustment. Therefore, a cost effective operation of the mill requires well defined grinding quality and particle size limits. Simple as this task sounds, it is difficult to realize in practice due to the above mentioned variability.

Next to the apparent mill related issues, the coal particle size spectrum and - also very important - the air-fuel ratio (AFR) have a significant impact on the combustion process inside a steam generator. They influence ignition delay, combustion efficiency and LoI, the NO_x and CO emission levels as well as the slagging and fouling tendencies. By influencing the devolatilisation rate and the composition of volatiles at the burner the ignition and flame properties are determined which in turn affect e.g. the NO_x levels. This aspect is especially relevant for low-NO_x type burners. Also, small, medium and large particles have different flow characteristics and vary in their furnace residence times. Since the heat balance and combustion time of a coal particle depends on its size, some particles may still be heated beyond their ash melting point or even undergoing reaction at their surface when entering the convection pass heating surfaces. In any case, the furnace exit gas temperature (FEGT) plays an important role when it comes to slagging and fouling. The carbon-in-ash level or loss of ignition (LoI) is yet another important property that is strongly affected by the size spectrum of the burning coal particles. Contributing to the problem, the particle-size spectrum is not a constant but may undergo rapid changes. Not only does it vary with the type of coal and composition (including water content) but also with the mill set-up and operating conditions and its wear and tear.

Despite the significant role that this property plays, there has yet not been a robust, easy-to-use and reliable measuring system that works both, online *and* inline. The method employed to date is to collect samples and then measure the particle size distribution in the laboratory. Thereby the collection of samples may even bias the result. Due to the cumbersome and costly method, the frequency of sampling and sieving is limited. Worse, the time lag between sampling and analysis makes it impossible to use the data for feedback control. Optimisation, if at all possible, will always be limited to static settings.

The measurement conditions inside a coal pipe are very demanding. They depend on plant characteristics and vary substantially. In lignite fired boilers for instance the pipe temperatures will be as high as 200 °C, while the flow is strongly abrasive, especially if the coal has a high sand content. High moisture content may further complicate matters. To make things even worse, the operating conditions may be continuously changing, i.e. coal composition, particle or load density, total mass flow etc. The particle load may reach up to 1000 g/m³. The particle stream will be distributed inhomogeneously and fluctuate in time. Maintaining the AFR in the required narrow limits becomes all the more a challenging task.

The laser based measurement system

A laser based system was designed and built that utilizes a time of transition technique rather than laser light diffraction. The system - EUcoalsizer - measures the particle size distribution, particle rate, velocity and temperature within a measurement volume that is placed at the tip of an insertable probe. By traversing the lance through the pipe, a spatially resolved distribution along the cross section of the coal pipe can be measured. In contrast to laser diffraction methods this measurement technique also covers large particles up to 4 mm, while the lower range covers particle sizes down to 20 µm. This is sufficient for most pulverized coal combustion furnaces. As we will see below, the particle velocity proves to be an essential add-on information as it allows determination of the mass flow of coal, air (or, more general the gas) and thus the AFR in the pipe.

The measuring probe has at its end an opening that constitutes the measurement volume, c.f. **Figure 1**. Coal particles crossing this volume intersect a lattice formed by closely spaced laser beams (f_0). The laser beams are emitted from one side of the measurement volume and the intermittency pattern is detected on the opposite side by a correspondingly spaced array of fibre optical detector elements (g).

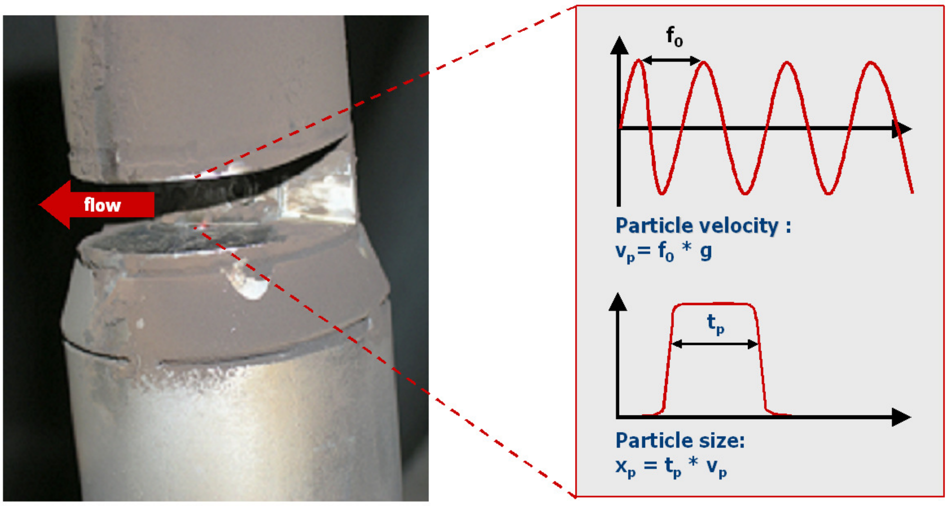

Figure 1: Probe after 100 h operation inside the pipe (left) and working principle (right)

This arrangement allows for the simultaneous, straightforward measurement of

- the particle velocity and
- particle size spectrum.

While the particle velocity (v_p) is determined through methods of frequency analysis, the particle size (x_p) is determined by the time of flight (t_p) and the particle velocity.

The procedure makes use of a high rate of single particle measurements. Tuneable statistical filtering methods look after double counts, particle coverage effects etc. The system stands out for its high measurement rate and excellent reproducibility. In contrast to other methods, e.g. laser diffraction techniques, no calibration of the system is required.

When developing the system, a Model-Based Design approach enabled efficient implementation and validation of sophisticated algorithms – the methods including system identification, rapid prototyping and Hardware-in-the-Loop simulations (**Figure 2**). All kinds of particle flows were modelled, our particular interest being with the difficult to analyse flow situations, i.e. overlapping particles, wide range of particles sizes etc. Knowing the 'correct' results from the simulations, the algorithms could be adapted and fine-tuned to tackle even the most challenging and otherwise inaccessible problem areas.

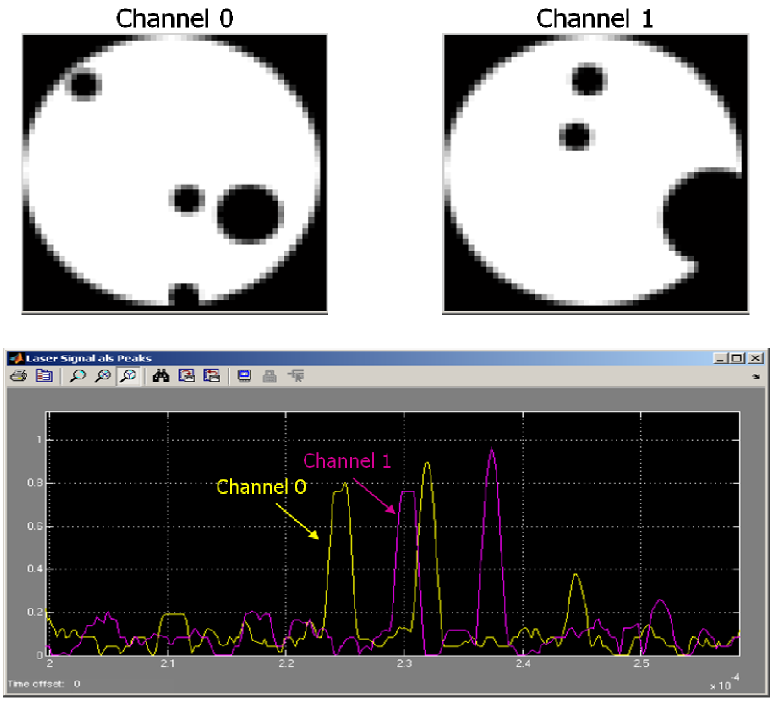

Figure 2: Model-Based Design; Rapid Prototyping and Hardware-in-the Loop Simulation. At top the coal particles passing fibre optical receiver channels 0 and 1 are depicted; lower part shows corresponding electrical signal after amplification

To make sure that the signal acquisition and processing is correctly modelled, a set of discs was manufactured that had bars and gaps with defined breadths at their outer rim (**Figure 3**). The disc(s) – several of them could be stacked atop each other – are mounted on a shaft and the outer rims of the discs rotate through the measurement volume of the probe. The bars and gaps produce alternating signals that emulate real coal particles in the range of 30 10^{-6} m (30 microns) up to 2 10^{-3} m (2.0 mm). The measured signals are then compared with the simulations and the transfer function of the electrical amplification and signal processing circuit is identified. Further, knowing the arrangement of bars and gaps on the disc enables direct verification of the given set-up.

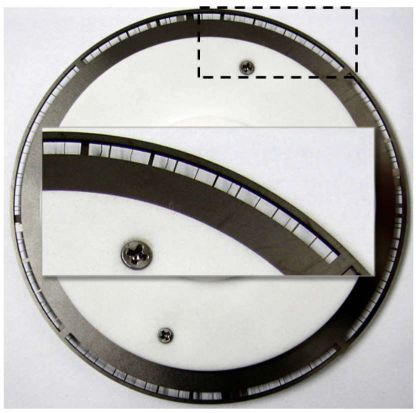

Figure 3: Disc for simulation particle flow; the inset shows the arrangement of bars and gaps

System set-up

The coalsizer system consists of a measuring probe mounted on an air-cooled lance and a control box which contains the pneumatic supply (purging and cooling air) and the electronics. Both parts are connected via a connector (**Figure 4**). The connection contains the air and power supply as well as the signal transfer to and from the lance. The coalsizer is operated from a sturdy, integrated toughbook.

The system is operational within one minute as it only has to be connected to power and the compressed air supply. Moving the equipment from one pipe to another can be done in just a few minutes and requires no shutdown of the system.

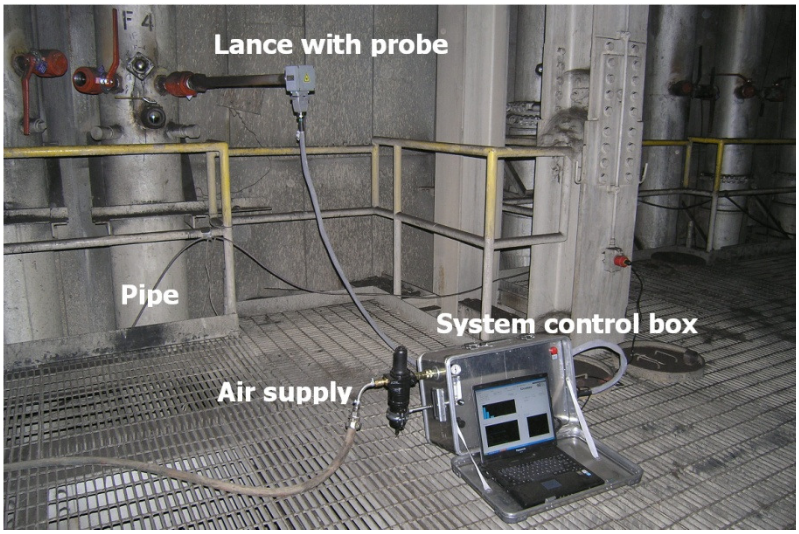

Figure 4: The system in operation

The system is designed in such a way that delicate opto-electronic components inside the probe are protected from thermal and mechanical impact. Small bursts of purging air keep the optics clean, while a temperature control at the tip of the probe helps to avoid condensation and accumulation of wet coal. System operation is completely automated and in the case of any problems the operator is immediately alarmed. To facilitate system handling and data allocation, the lance position is automatically recorded. Data analysis, evaluation and data storage are handled by the process PC. Automatic report generation according to user defined requirements is a helpful feature that is also included. Handling is very easy *via* an intuitive graphical user interface and the results can be readily interpreted (**Figure 5**).

Figure 5: Standard user interface with online display of results

A systematic series of test measurements was done in different power plants and with different coal types to validate the reliability of the system by simultaneously taking the traditional route of sampling and sieving. The installation is very easy, and usually no calibration is necessary. The results show a very good match with the sieving results while having far better reproducibility.

Typically, a single point measurement requires only one minute. The analysis is done online and the results visualized e.g. as

- discrete classes of particle distribution and cumulative particle distribution
- particle distribution of any self-defined sieving class
- velocity distribution
- particle load density and mass flow

Case study 1

Mill optimisation (lignite-fired 600 MW TPP, Central Europe)

The task was to homogenize the grinding quality of the eight mills of a 600 MW lignite fired boiler and optimise the particle size distribution behind the separators. Thereby the speed control range of the mills was to be extended as they were constantly running at maximum speed, leaving no room for adjustments. Since the boiler operating conditions and coal quality varied significantly, an offline optimisation based on traditional sampling methods was not feasible. Rather the online capability of the coalsizer was utilised. The system was applied in the coal pipe directly behind the separators. During the measurements the mill parameters (speed and load) and the adjustments of the separators were systematically varied and the effects of these variations could be analysed online. This allowed for a very efficient real-time optimisation of the separator adjustments in such a way, that an acceptable speed control range could be established:

- Increase of separator efficiency and particle size homogeneity (reduction of standard deviation in particle size)
- Reduction of mass circulation rate through separator

- Achieving a suitable control range for each mill

Figure 6 shows the online result of particle size distribution during parameter optimisation after separator. While the distribution with parameter setting 2 show a large fraction of large particles the change parameter setting in case 1 allow to achieve higher fractions of smaller particles.

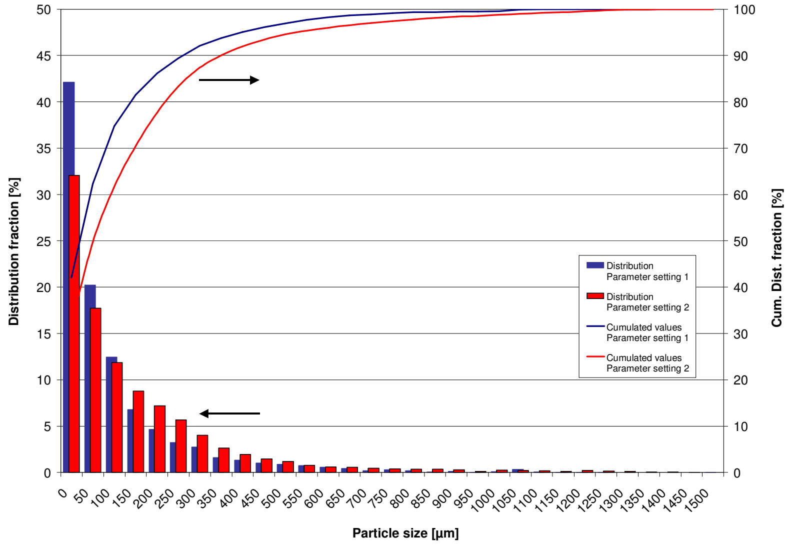

Figure 6: Particle size distribution with different parameter settings of mill and classifier

Case study 2

Coal flow balancing and mill maintenance (coal fired 300 MW TPP, South East Europe)

The objective of this project was to equalize and balance the mass flow rate of coal dust to the burners. It is a well established fact that meandering streaks of coal dust can cause significant distortions in the distribution of coal to the burners. Since the flow characteristics of the coal dust are also influenced by the particle size distribution the mill settings were systematically modified to also take care of this variability. The cross sections in the pipes were scanned and the particle density distribution and particle velocities were measured. With this, the mass flow rates in the pipes could be estimated as a function of load, mill speed and separator position.

Apart from the well balanced coal mass distribution, the wear of the mills could also be evaluated by looking at the particle size distribution. Typically, with increasing wear, the large size fraction of particles increases markedly. To some extent mill parameters can be adjusted such, that changes of the particle size spectrum can be compensated. It could also be shown, that the mill with the most severe attrition had to be overhauled after only 300 hrs. of operation, while another mill was able to run for more than 6,000 hrs. before grinding quality reached a predefined limit. Thus, the coalsizer can contribute to establishing a condition based maintenance management.

In **Figure 7** illustrates the local distribution of particle size fractions smaller than 125 µm and larger than 1000 µm at different mill loads.

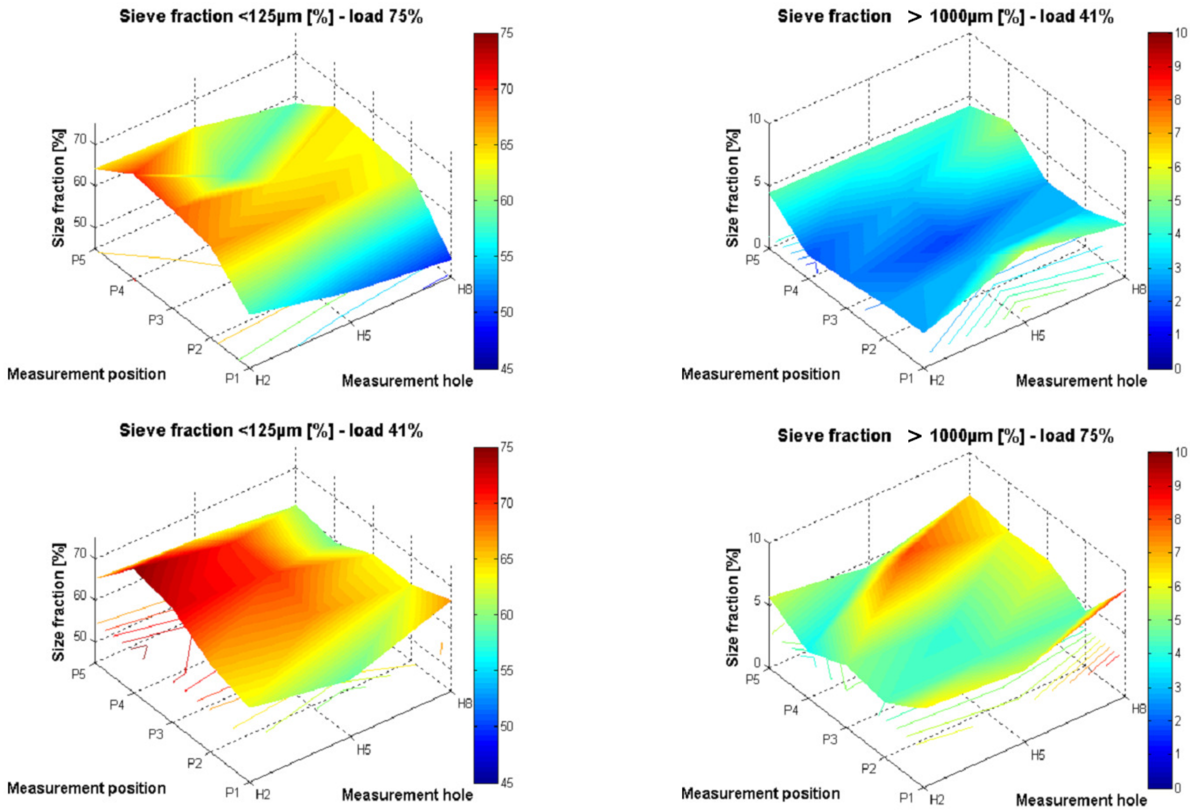

Figure 7: Flow field and particle size distribution in a coal pipe

Case study 3

Coalsizer as an integral part of 'Best Practices' O&M (coal fired 540 MW TPP, United States)

As mentioned in the previous examples, the coal fineness and mass flow balancing plays a very important role in the combustion process. Therefore it is advisable to establish frequent measurements within an operations management scheme aimed at maintaining 'best practices' – if only the effort can be kept at a reasonable minimum. The objective is to perform reliable measurements in the shortest of time with a minimum of personnel resources.

Online measurements of the fineness, velocity and mass flow of coal particles inside the pipes of a 540 MW unit were done using the coalsizer. The measurements were carried out in five pipes with two rectangular measurement ports for each pipe. The entire measurements were completed in 2 hr 40 min. This means that one mill with four pipes can be analysed within two hours (two ports at each mill) or in only one hour when using only one port.

Each pipe has two ports installed in a rectangular position, and each port has a 2.5'' ball valve. A special over-pressure adapter was mounted to prevent coal dust leakage (**Figure 8**). The lance is pushed through the adapter into the closed ball valve. After opening the ball valve the lance enters the coal pipe.

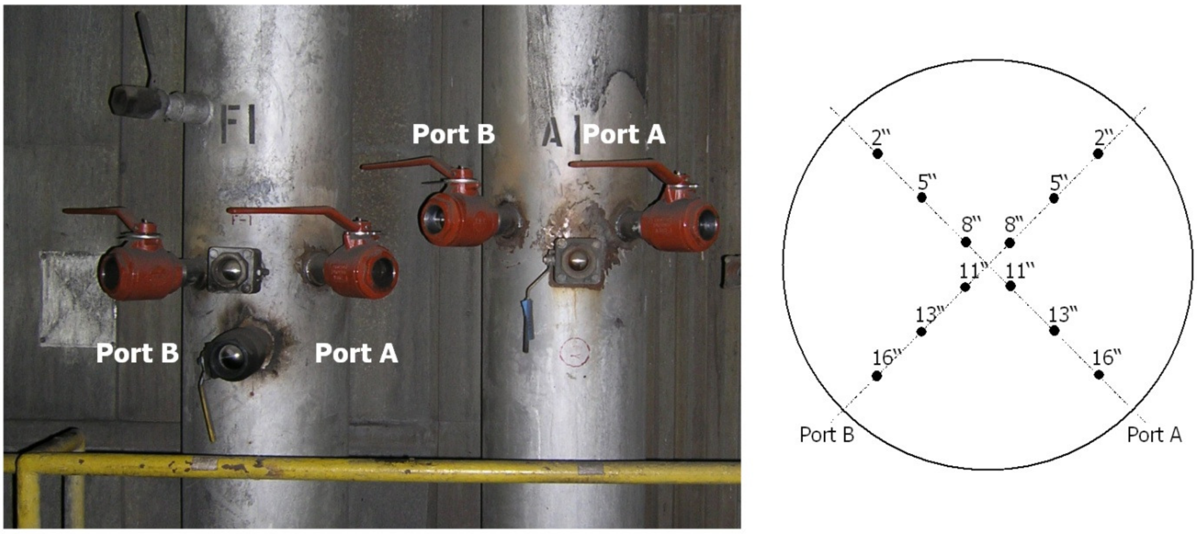

Figure 8: Ports with 2.5'' ball valves (left), arrangement of measurements (right)

On average seven positions in the pipe are measured. Thereby, a sufficient number of particles had to be sampled at each location (her set to 100.000 particles). The measurement at each location lasted approx. 1:40 minutes. Thus, one coal pipe can be handled in less than ten minutes (or five minutes if one limits the measurement to only one port). The results are given in the **Tables 1-3.**

Compared to the standard sampling technique (four pipes in eight hours) the online coalsizer cuts down the required time to 20 %, not counting the time to analyse the probe. The results clearly prove the usefulness of online coal fineness measurements being an integral of best practices O&M:

- Easy system set-up and handling
- Very short measurement times
- Immediately available results without post-processing (sieving, laboratory analysis, reporting etc.)
- Direct cause-and-effect relationships for tuning mill and classifier adjustments
- Tuning coal-flow distribution and optimising coal-air ratio
- Time and money savings - measurements can be done very frequently

Note: When using adjustable orificing valves a customized multiple probe arrangement will offer extra benefits.

Particle fineness

Mean values were calculated form single point measurements to compare with standard sampling/ sieving method.

	F#1	F#2	F#3	F#4	A#4
	%	%	%	%	%
50 mesh	99.2	98.3	98.4	98.8	97.1
100 mesh	86.6	80.0	81.2	89.2	79.0
200 mesh	47.7	47.4	42.1	51.0	45.2

Table 1: PC fineness (averaged values) of coal pipes F#1 - F#4 & A#4

Particle velocity

The mean velocity from the velocity readings of all F pipes is 19.7 m/sec (64.6 ft/sec). **Table 2** show the mean velocity in each pipe and their standard deviation.

	F#1	F#2	F#3	F#4	A#4
	m/sec (ft/sec)	m/sec (ft/sec)	m/sec (ft/sec)	m/sec (ft/sec)	m/sec (ft/sec)
Mean velocity	20.4 (66.9)	17.8 (58.4)	19.4 (63.6)	21.1 (69.2)	19.1 (62.7)
Std. deviation	4 %	-10 %	-1 %	7 %	-

Table 2: Velocity distribution and standard deviation in measured pipes

Mass flow

The mass flow can be calculated from the particle size and velocity distribution. Determination of the absolute mass flow will require geometric calibration and parameter adjustments (form factors, coal density etc.). **Table 3** shows the *relative deviation* of the mass flow in pipes F#1-F#4 to their mean value, which, under the given circumstances is a more reliable value. In practical circumstances this will be the relevant information.

	F#1	F#2	F#3	F#4
	%	%	%	%
Mass flow dev.	6	- 13	19	- 12

Table 3: Relative mass flow deviation in each pipe to the average mass flow in pipe F#1 - #4

All measurements match with the readings of the standard probe sampling and sieving method (ASTM D 197) – without any prior system adjustments or calibrations. Moreover, the spatial resolution and the additional information given by the velocity distribution (not shown here) provide valuable information about unequal distribution of coal fineness and velocities and mass flows.

Case study 4

Air-Fuel ratio measurement inside the pipe (coal fired 750 MW TPP, Germany)

The unit is the largest slag tap boiler of its kind. The coal is of the anthracite type with co-combustion of meat and bone meal (MBM). NO_x levels are reduced via SCR. Effective control, balancing and monitoring of the air and fuel flows, their distribution, as well as the coal particle fineness adjustment is required for

- Correct AFR at the burners
- Reduction of NO_x and carbon-in-ash
- Balanced FEGT boiler temperature profile
- Avoiding pipe plugging and limiting pipe erosion

One of the main causes of NO_x emissions and carbon-in-ash is the imbalance of the air-fuel ratio (AFR) and the quality of the pulverization. A low AFR contributes to high carbon-in-ash levels, while a high AFR contributes to NO_x formation. Since the unit burns MBM, there are particular combustion regulations which also have to be met. Due to the boiler design, the coal pipes run horizontally over long distances and there is a risk of particulates falling out and causing dangerous pipe blockages. Although there is a micro-wave based mass flow measurement system installed, the results do not always seem to be correct. **Figure 9** shows how EUcoalsizer can be applied to a horizontal pipe.

Figure 9: Measuring in a horizontal pipe

Measurements were made in all the pipes of a given mill, thereby not only looking at the overall mean data but also at their spatial distribution. During the measurements the hopper settings were adjusted such that there was an increase of the mass flow of coal. Looking at the velocity distribution in the pipes, **Figure 10** we see that there is a pronounced profile with the higher velocities in the upper pipe regions and the lower velocities in the lower regions. Increasing the coal flow hardly alters velocities, though the profiles are slightly altered.

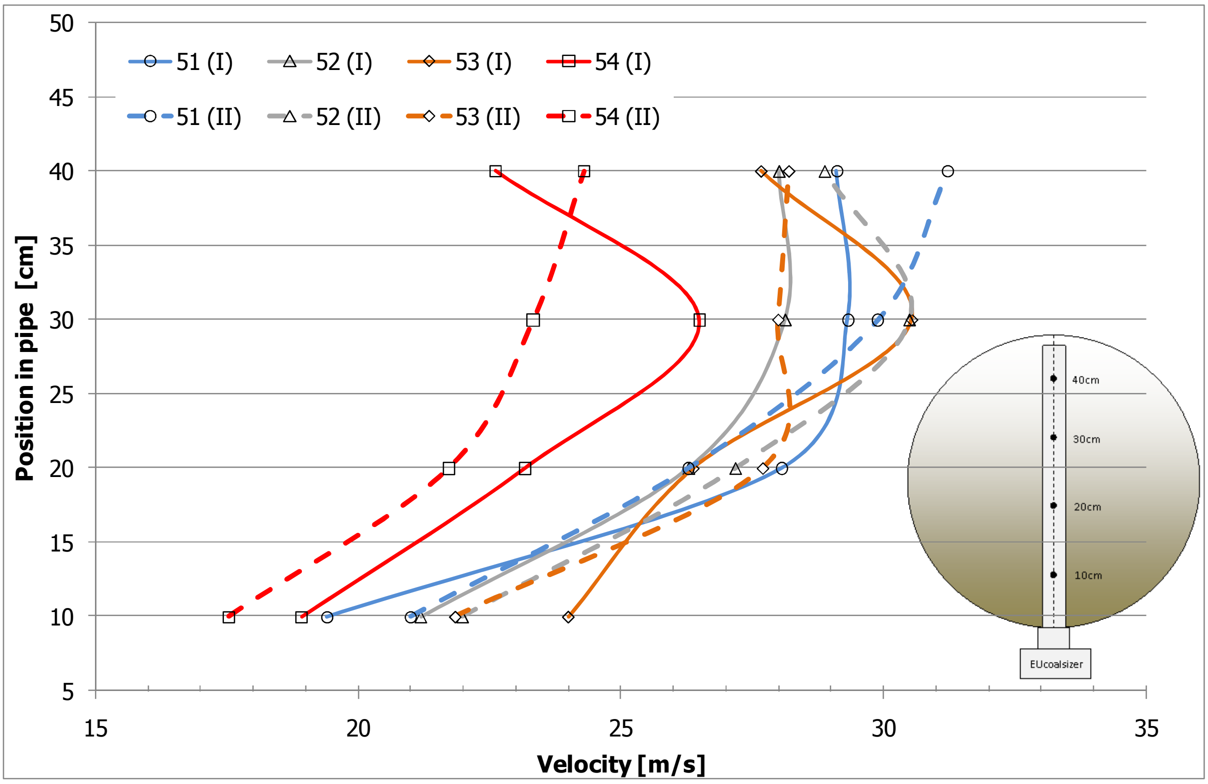

Figure 10: Spatial velocity distribution in the pipe, I) refers to original flow velocity and II) to flow velocity after increasing hopper load

The fraction of particles > 90 µm is an essential parameter for the plant operators to evaluate combustion. **Figure 11** depicts the cross-sectional distribution of the particle fractions > 90 µm. As would be expected, the larger particles are concentrated in the lower pipe section which explains the lower velocities shown above. Interestingly, when the hopper load is increased, the profile becomes more evenly distributed from the top to bottom section of the pipe, while the magnitude of the overall fraction > 90 µm increases.

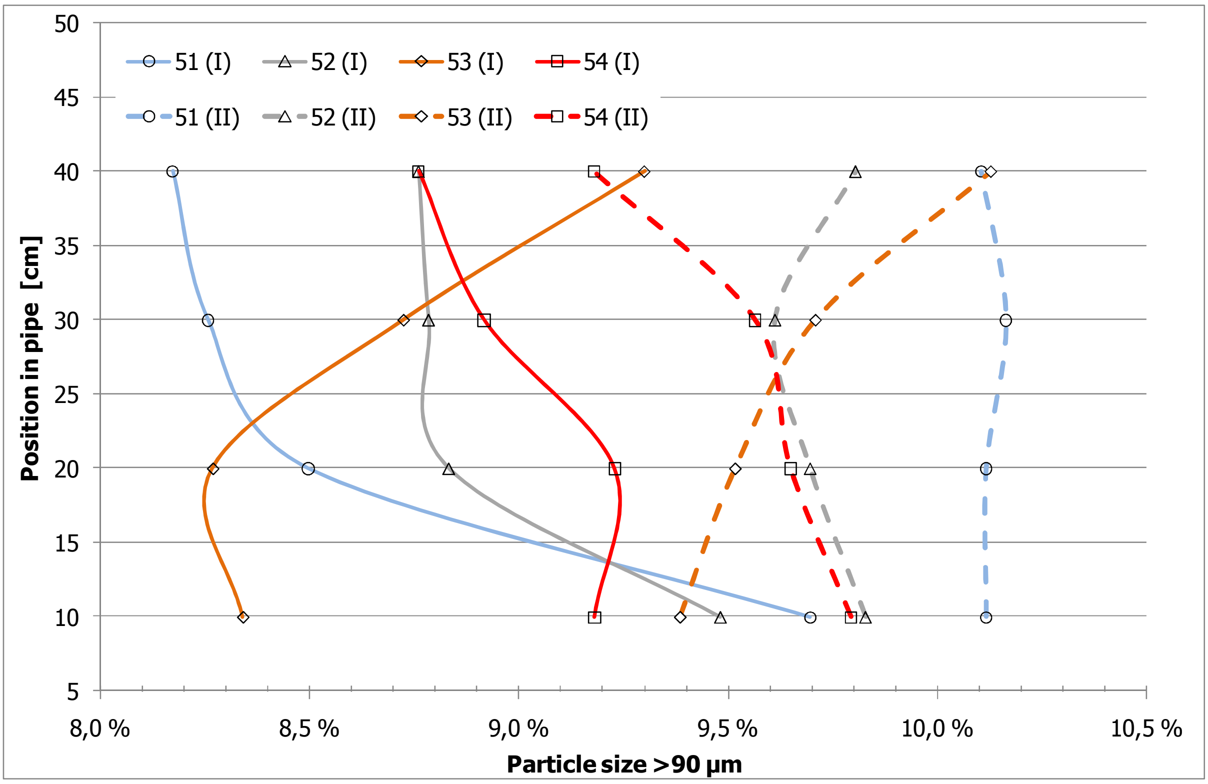

Figure 11: Spatial distribution of particle fraction > 90 µm in the pipe, I) refers to original flow and II) to flow after increasing hopper load

The mass flow of the coal and the carrier gas – made up of air and flue gas – is shown in **Figure 12**. Clearly, when the hopper load is increased (I -> II), the mass flow of coal increases, while the mass flow of the carrier gas remains nearly constant.

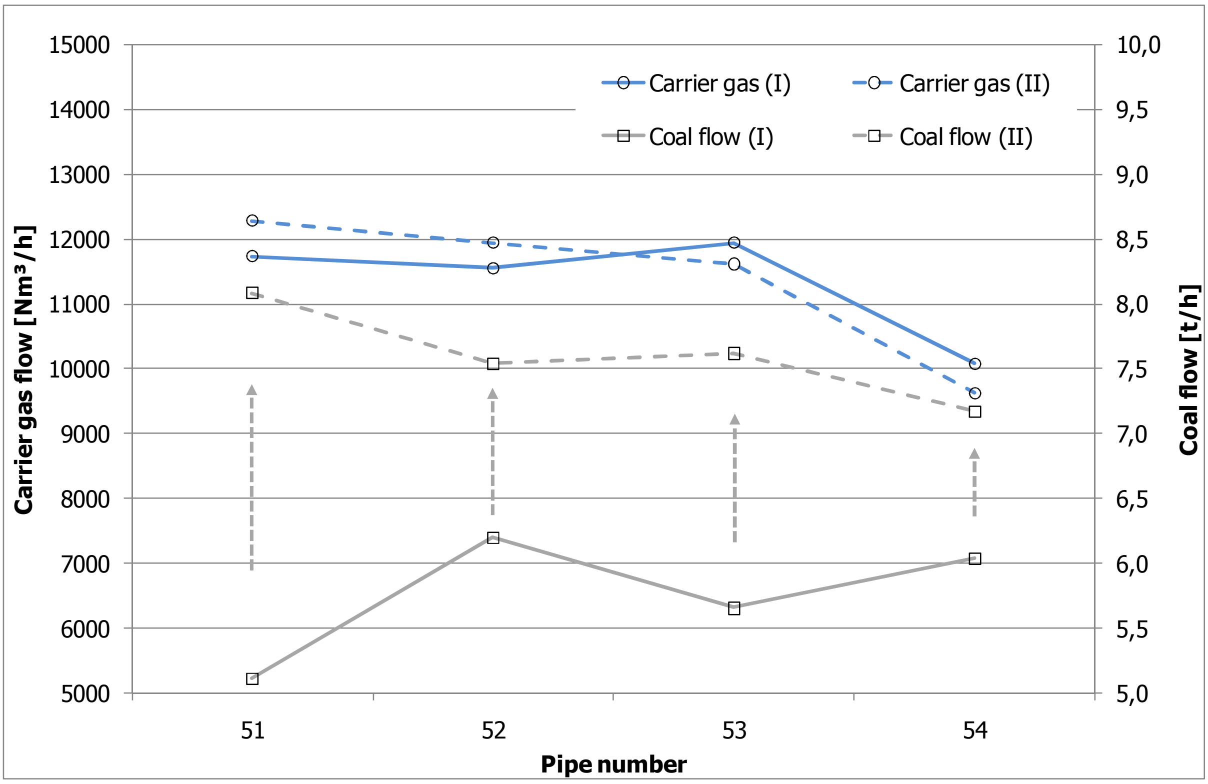

Figure 12: Measuring the mass flows of coal and carrier gas in the four different pipes of mill # 5; I) refers to original flow and II) to flow after increasing hopper load

However, increasing the mass flow of coal increases the fraction of particles fraction > 90 µm, c.f. **Figure 13**.

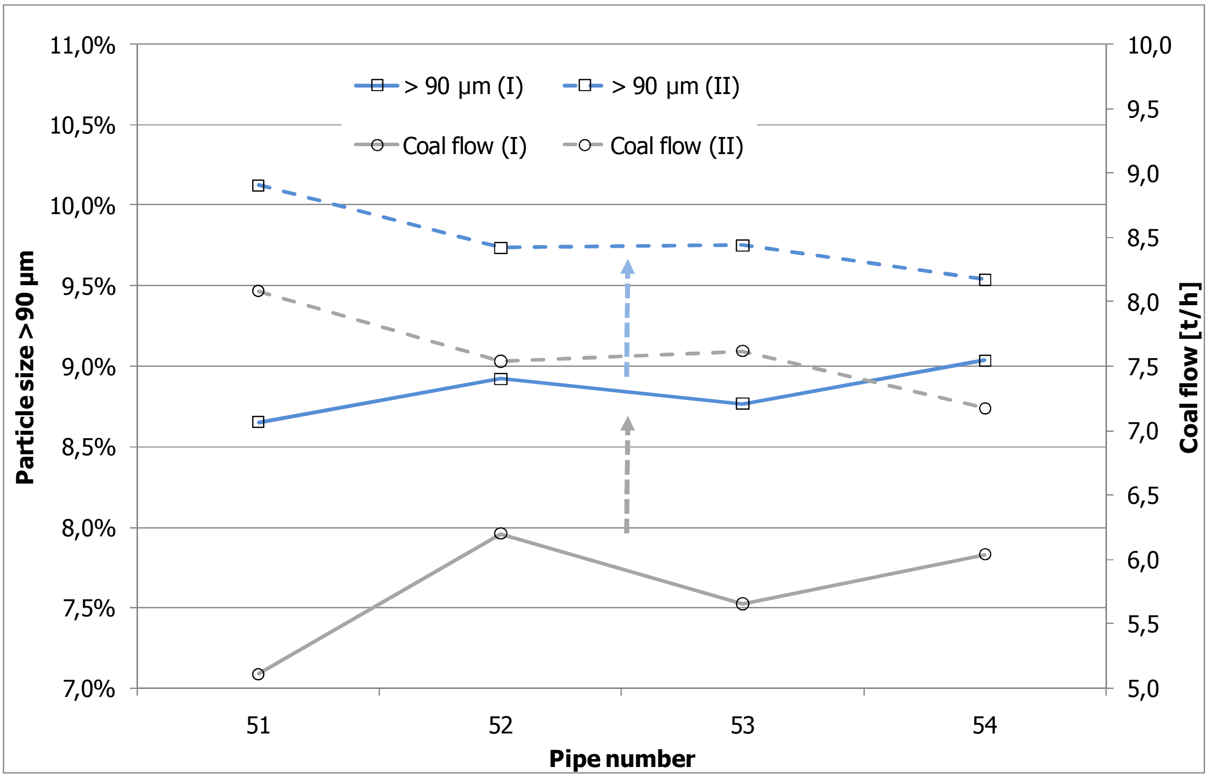

Figure 13: The fraction of particles > 90 µm increases with the mass flow of coal

Having measured the mass flows of coal and carrier gas, we finally determine the AFR in the pipe. EUcoalsizer cannot measure the gas composition, so this information has to be provided from another source. A straightforward and simple way – if not very accurate – is through the energy balance at the mill. We know that the carrier gas temperature results from the mixing of primary air with flue gas and coal inside the mill, so

$$\dot{m}_{carrier\ gas} = f(\dot{m}_{coal}, \dot{m}_{flue\ gas}, \dot{m}_{primary\ air}, T_{coal}, T_{primary\ air}, T_{flue\ gas}, T_{carriergas})$$

Also,

$$\dot{m}_{carrier\ gas} = \dot{m}_{flue\ gas} + \dot{m}_{primary\ air}$$

And, with some minor assumptions regarding coal composition and moisture content, the ratio of carrier gas and primary air can be determined. Knowing this property we can calculate the AFR inside the pipe, **Figure 14**. Additionally, the velocities in the pipe are depicted.

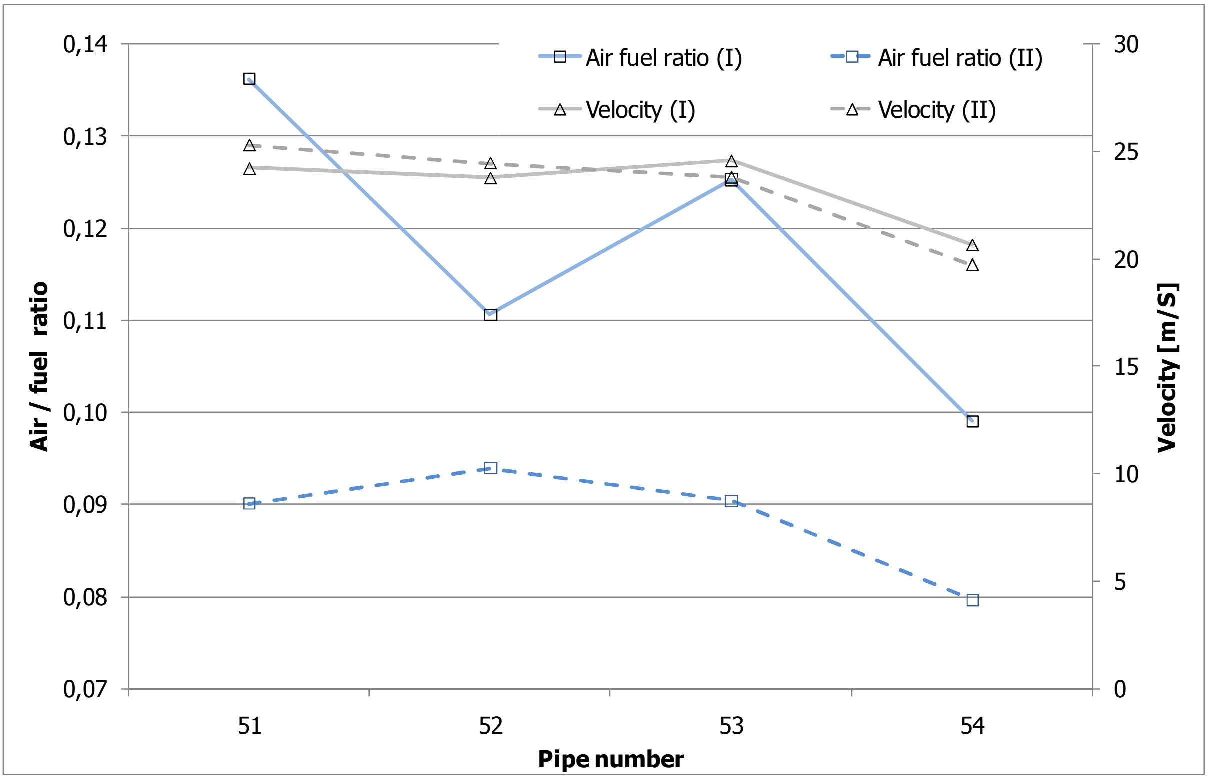

Figure 14: Primary AFR and flow velocity inside the pipe

Summary

EUcoalsizer is a reliable system to support the boiler operation staff engineers in their daily optimisation tasks. The benefits are

- Optimised combustion (minimise NOx and LoI)
- Increased boiler efficiency
- Correct air-fuel ratio at the burner
- Balanced coal flow
- Reduced slagging
- Avoidance of pipe blockage

All these benefits are made available at significantly reduced time and cost while carrying through the measurements.