Advanced combustion monitoring tools for efficient, clean and flexible utility boilers

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Standard equipment installed on large utility boilers rarely allow for an online monitoring of key combustion parameters such as burner air and fuel distribution, burner stoichiometric coefficients, Furnace Exit Gas Temperature (FEGT), or solid fuel Particle Size Distribution (PSD). These parameters however influence the combustion efficiency, the emission of pollutants, the quality of the combustion by-products, as well as the load and fuel flexibility of the unit. Advanced measurement tools are now available on the market to accurately monitor those parameters online. They can be used for trouble shooting purposes, or permanent installation and integration in the boiler control system. This paper gives an overview of such devices used for trouble shooting and/or control in large scale power production units. Cases are presented. For all boilers, information that was not previously available to the operators have been brought to light and allowed for corrective actions leading to improved combustion balance. The EUFlame system gives an online, 2D image of the temperature field at the outlet of the furnace, while the EUSoft Air and the EUCoalFlow systems provide an online monitoring of the air and fuel flow rates to the burners. The EUCoalSizer system gives an instantaneous measure of the Particle Size Distribution without sampling and without lab analysis. Depending on the specific requirements for a given unit, the combination of several of these tools addresses the need to retrieve more information on the combustion process, leading to increased performances and flexibility, as well as additional revenues or substantial savings.

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1 Introduction

It is rather confusing to notice that, although combustion obviously plays a central role in thermal power plants, it is also one of the least monitored processes. While the thermodynamic states of the working fluid are accurately measured all along the thermal cycle on the water-steam side, several major parameters related to combustion are only approximately known. Even basic quantities like air-fuel ratios are not easily retrieved by the operators of a pulverised-fuel boilers (PF-boilers). Utility boilers unfortunately remain black boxes for many operators.
On the input side, the fuel flow rate is known, within a certain degree of accuracy, at the inlet of each mill, but not at the level of the burners. It is then assumed that the fuel is evenly distributed downstream of the mill. The amount of air injected in the boiler is measured for each burner in some boilers, sometimes with a questionable accuracy, while only the total primary and secondary air flows are known in some others. As will be shown here, the computation of local air-fuel ratios is therefore subject to a lot of uncertainties. The quality of the fuel preparation in terms of particle size distribution is not easily accessible neither: it requires time-consuming sampling and off-line lab analysis. The organic and inorganic composition of the fuel is also only known after some delay through lab analysis. These results are sometimes available after the fuel was injected in the boiler.
As far as the outputs of combustion are concerned, oxygen (O_2), carbon monoxide (CO) and nitrogen oxides (NO_x) concentrations are measured in the flue gas path, using multiple sampling points in order to approach their true average values. Their values in the furnace are not measured. The cross section average Furnace Exit Gas Temperature (FEGT) is generally unknown, not to mention its 2D spatial distribution, or even the temperature field inside the furnace. A limited number of thermocouples located close the walls of the boiler are supposed to provide the operator with an image of FEGT, that can be used to draw conclusions on relative trends at best.
The quality of the combustion process however has a huge influence on the performances of the power plant, in several respects: efficiency (steam temperature, de-superheater sprays, loss of ignition…), pollutant emissions (NO_x, CO, dust), availability (boiler slagging, fouling, corrosion, …), operational expenses (NH_3 consumption, steam consumption, …) and market value of by-products (ash quality[1]).

[1] Cfr., for instance, the European legislation on fly ash quality (EN450)

Given the limited monitoring tools available, the operators need to rely on the initial commissioning of the boiler and its auxiliary equipment (air flow measurement calibration, fuel flow balancing, ...) and/or on posterior, time-consuming re-calibrations to assume that the combustion process is balanced, unless obvious issues like boiler failure, high unburnt carbon content, high/low/unbalanced O_2, or high/low/unbalanced NO_x emerge.
In the current context of energy transition, thermal power plants however face a growing demand for fuel- and load-flexibility. This is obviously not compatible with uncomplete feedbacks on combustion based on partial, sporadic calibrations. In order to be able to burn different fuels or fuel mixtures at various loads, the operator should have a constant, complete overview on the inputs and the outputs of the combustion process.
Efficient online combustion monitoring in large utility boilers is therefore a key issue to solve to move towards efficient, reliable, clean and flexible power plants in the future.
This paper is concerned with the description of innovative tools available on the market to monitor air distribution, fuel distribution, FEGT and particle size distribution online in large utility boilers. Experimental results are presented.

2 Fuel distribution

The standard way to monitor the amount of solid fuel fed into a PF-boiler is to measure the flow rate delivered by the feeders to the mills. Inside the mills, the solid fuel is pulverized and entrained by the preheated primary air stream to the burners. During commissioning, the fuel distribution between the burners is generally checked using manual flow rate measurements based on isokinetic sampling. When the fuel flow rate is kept constant during the whole measurement procedure, this time-consuming technique can provide a reliable measurement of the particle flow rate for a given load. The fuel flow rate balance between burners can then be tuned by modifying the relative pressure drops in the feed lines, through the adjustment of diaphragms. The obtained balance is however dependent on the type of fuel, the selected particle fineness and the load. Other parameters, like progressive coal particles deposition in the horizontal sections of the lines, can also impact the fuel distribution. The homogeneity of the fuel distribution is not always re-assessed during the lifetime of the boiler, and at best once or twice a year using isokinetic sampling. Isokinetic sampling measurements can also be carried out for trouble-shooting purposes (Blondeau, Rijmenans, et al. 2018).
Tools for online fuel distribution monitoring are however available on the market. The equipment used in this study is the EUCoalFlow system developed by EUtech, described in

detail in (Starke, Kock, et al. 2010) and mentioned in a recent report published by the IEA Clean Coal Centre as part of the new equipment allowing for optimised boiler performances (Wiatros-Motyka 2016). It is based on the Doppler effect: microwaves are emitted and reflected on the moving particles inside the pipes, see Figure 1. 2–3 sensors are generally installed per coal feed line to cover the whole cross section, see Figure 2. The system can be mobile, or permanently installed, with a link to the control system.

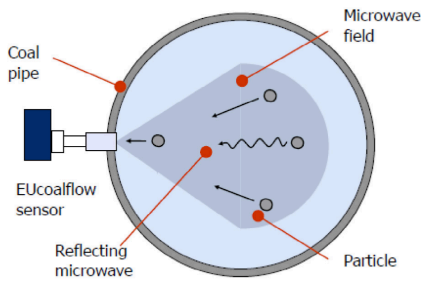

Figure 1: Principle of the EUCoalFlow system for pulverised fuel flow rate measurement (Blondeau, Rijmenans, et al. 2018)

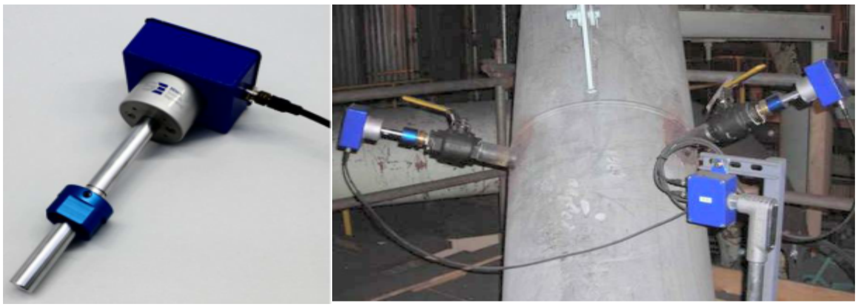

Figure 2: EUCoalFlow system microwave sensors

The mA signal retrieved from the sensors is a linear function of the particle mass flow rate, but the absolute flow rate value is not directly measured. The absolute values can be obtained after calibration, by using the total flow rate fed to a mill in steady state as reference. Figure 3 illustrates the agreement between the sum of the flow rates measured in each pipe and the total feeder flow rate. The short delay between the load transition experienced by the feeder and the pipes is due to the buffering effect of the mill itself. The estimated error in steady state phases is less than 4%. The precision (repeatability) of the measurements is lower than 2% (Blondeau, Rijmenans, et al. 2018). The rule of thumb given in Table 1 can be used to assess the quality of fuel distribution between burners.

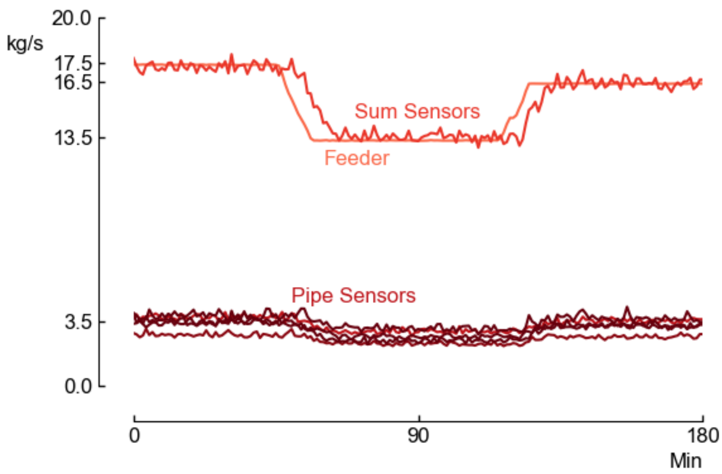

Figure 3: Agreement between the total feeder flow rate and the sum of the individual pipe flow rates after calibration (Blondeau, Rijmenans, et al. 2018)

Deviation to the mean flow rate	
< 5%	Excellent
5-10%	Very good
10-15%	Acceptable
15-20%	Poor
20-25%	Problematic
> 25%	Highly problematic

Table 1: Qualitative assessment of the fuel distribution imbalance between burners fed by the same mill (Blondeau, et al. 2018)

3 Air distribution

As stated in §1, not all boilers are equipped with air flow rate measurements per burner, not even per row. When they are, velocity measurement techniques (like multiport Pitot tubes) are generally preferred to obstruction flow meters (like Venturi, nozzle or orifice devices), only considered for total flow measurements at the outlet of the fans (Blondeau, Rijmenans, et al. 2018). The local measurements are calibrated during commissioning using manual, grid-measurements. Correction factors are then applied to account for the imperfect location of the measuring orifices. The authors have seen correction factors higher than 30%, sometimes up to 50%, in the control systems of large utility boilers. Such corrections should normally be avoided, and the correct installation of the measurement device should be checked again.

Measurements using such large correction factors cannot reasonably be trusted in conditions other than those at which they have been calibrated: for other loads, large discrepancies between the measured value and the actual flow rate can be expected. The local measurements are considered less reliable than the total flow measurements performed at the outlet of the fans. Discrepancies between the measured total flow rates and the sum of all the local flow rates can be observed, as will be showed in this study.

Innovative, model-based methods can however be used to complete missing information on air distribution or to challenge existing local measurements without installing additional devices. The commercial EUSoft Air system developed by EUtech was used in this study (Turoni, et al. 2011). In those approaches, a model of the aeraulic network of the boiler is trained based on three types of data:

1. The local pressure measurements;
2. The damper openings;
3. The reliable air flow measurements that are available (e.g. total air flow measurements).

Using this information, it is possible to determine the pressure drop characteristics of each portions of the air distribution system. Equivalent flow resistances are then determined for different branches of the network, as illustrated in Figure 4. Once the model is trained for a specific boiler, the local air flow rates can be computed based on new, online data (e.g. fan load, pressures, damper openings, etc.) (Blondeau, Rijmenans, et al. 2018). The EUSoft Air system can be used offline, using data retrieved from the control system, or online, with a direct link to the control system.

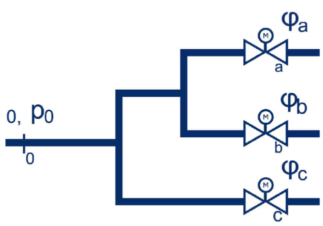

Figure 4: Principle of the EUSoft Air system – the aeraulic system of the boiler is characterised by equivalent flow resistances

Figure 5 illustrates the case of boiler for which the local measurements systematically overestimated the air flows. The sum of the local flow rates calculated by the EUSoft Air system are in agreement with the total flow rate delivered by the Forced Draft fan, while the sum of the existing, local measurements is approximately 15% above this value.

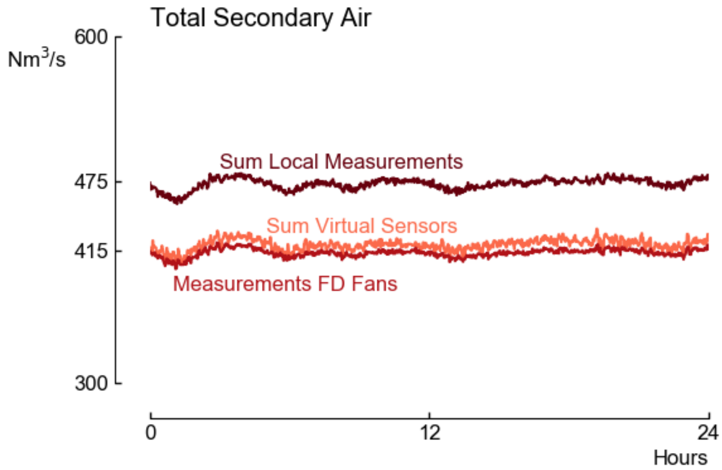

Figure 5: The sum of local air flow measurements overestimates the total air flow with 15%, while the sum of the values computed by the EUSoft Air system is in agreement with the total flow rate delivered by the FD fan (Blondeau, Rijmenans, et al. 2018)

4 Particle Size Distribution

Injecting too coarse particles in the furnace may have an important impact on the combustion efficiency, the emission of NO_x and CO, the good operation of the ElectroStatic Precipitators (ESP), ash quality[2], and the availability of the boiler (slagging and fouling issues). The variation of the Particle Size Distribution (PSD) with the fuel composition, its moisture, the primary air flow through the mills, the mill settings and the boiler load is sometimes neglected by operators, and the PSD is not always monitored in a regular way. The standard procedure to measure the PSD is to sieve a representative amount of coal particles sampled at the outlet of the mill. This procedure is time consuming, and only gives an image of the PSD for specific conditions, considering that the sample is representative.

Laser-based systems now allows for an immediate PSD measurement (without sampling) by introducing a probe in the feed lines. Such systems allow for a direct monitoring of the impact of any process modification on the PSD. Using such an instantaneous feedback, the online optimisation of this crucial parameter becomes possible. The principle of the EUCoalSizer probe developed by EUtech, already presented in detail elsewhere (Starke, Schulpin, et al. 2007), is illustrated in Figure 6 and Figure 7: each individual particle flowing in the

[2] Cfr., for instance, the European legislation on fly ash quality (EN450)

measurement volume is detected by a stream of parallel laser beams. The range of detection of the EUcoalsizer probe is 20 µm – 4 mm. For a single PSD measurement, the total amount of particles detected before the sample is considered representative is 10^5. The estimated error on particle size measurement itself is less than 3%. The precision (repeatability) of the measurements is lower than 1.5% (Blondeau, Koch, et al. 2016).

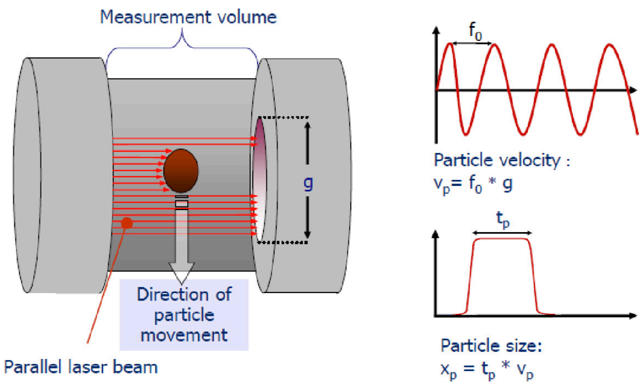

Figure 6: Working principle of the EUCoalSizer probe (Blondeau, Koch, et al. 2016)

Figure 7: The EUCoalSizer system, including the probe

From the measured sizes of the 10^5 detected particles, all the detailed characteristics of the PSD can be retrieved, including of course typical specified values like the ratios of particle smaller than 75 µm or larger than 300 µm, as illustrated in Figure 8.

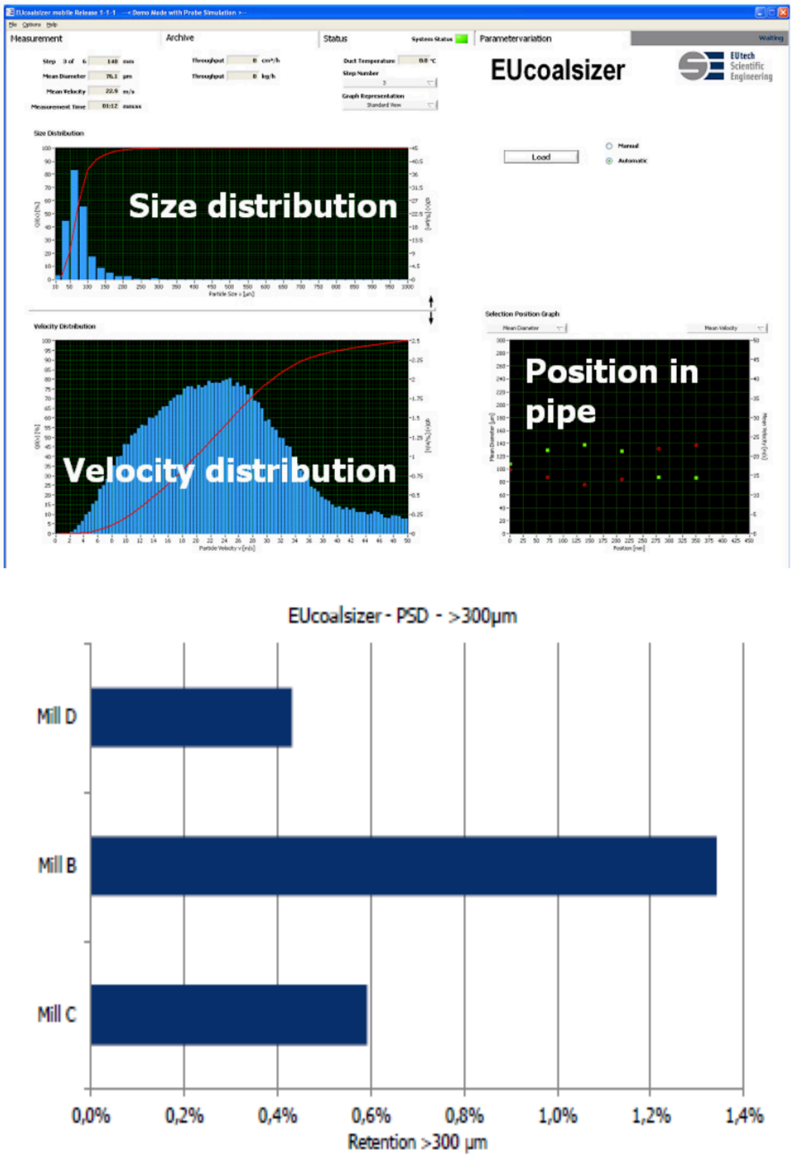

Figure 8: Examples of detailed results and general PSD characteristics retrieved from EuCoalSizer measurements

5 Furnace Exit Gas Temperature (FEGT)

FEGT is a key output of the combustion process. It is the consequence of two competitive mechanisms: it increases with the amount of heat released in the furnace and decreases with the amount of heat transferred to the evaporator. It is a major parameter considered in the design of furnaces, that is surprisingly not properly monitored with standard equipment.

In case of slagging or fouling issues in the first convective heat exchangers, high carbon content in the fly ash, abnormal superheated/re-heated steam temperature or high de-superheater spray flow rate, the average FEGT needs to be checked. Also, the 2D temperature field at the outlet of the furnace is very useful to monitor, in order to check that the flame is well centered in the furnace and will not cause wall tube damages due to an unbalanced heat flux.

By using a network of infrared pyrometers, the operator can monitor the 2D FEGT field online from the control room. The EUFlame system developed by EUtech is illustrated in Figure 9. Using typically 4 to 10 pyrometers, the 2D temperature field can be reconstructed. A typical result is shown in Figure 10. The main advantage of EUflame is that the same sensors are used as emitters and receptors, avoiding the need for a perfect alinement of 2 sensors across the furnace section. The system can be mobile, or permanently installed, with a link to the control system.

Figure 9: An EUFlame pyrometer

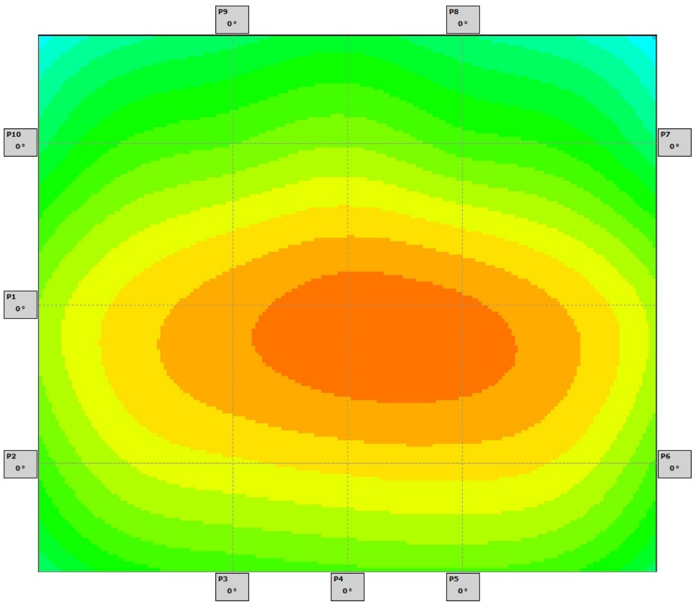

Figure 10: FEGT 2D field reconstructed based on the signals from 10 IR-pyrometers installed at the nose of a utility boiler

6 Applications

6.1 Secondary air flow balance

Using the EUSoft Air system alone (offline or online), one can easily and quickly point out air flow imbalances, whether by adding new local measurements, or by challenging existing local measurements. It can happen that local flow rate values sent to the control system show no imbalance, while it is actually the case. New information is then available to the operators.

Once abnormal discrepancies have been observed thanks to the EUSoft Air system, targeted, corrective actions can be carried out, with an immediate feedback on the results for an efficient optimisation. Using conventional, manual Pitot-tube measurements is much more time-consuming and dramatically increases the duration of the correction process.

Potential causes for hidden air flow imbalances are: biased damper position compared to the actuator, biased damper position feedback (if any), biased flow measurement due to poor pressure transmitter calibration, wrong signal treatment, excessive correction factors, …

Figure 11 illustrates an initial discrepancy and a final agreement between existing local flow measurements and the virtual sensors of the EUSoft Air system, for a large-scale coal-fired power plant.

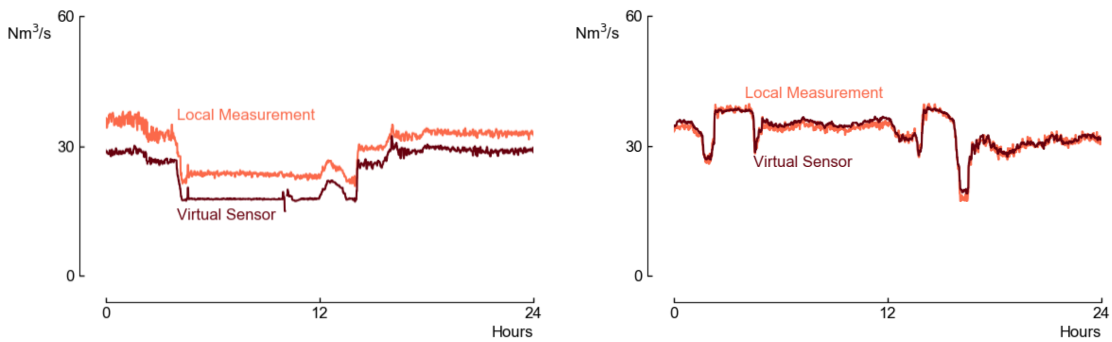

Figure 11: Examples of discrepancy and agreement between an existing measurement and a virtual sensor during the secondary air flow balancing of a large-scale coal-fired power plant (Blondeau, Rijmenans, et al. 2018)

By systematically adjusting the most problematic secondary air injection points, one can quickly improve the balance, as shown in Table 2 for the same power plant: these results were obtained within a few days.

Imbalance (Left-Right)	Good practice	Initial	Final
Δ Total secondary air [kg/s]	<10	~ 20	3–7
Δ FEGT [°C]	<10	~ 10	2–7
Δ O_2 [$\%_w$]	<0.5	~ 1	0.3–0.7
Δ primary NO_x [ppm]	<10	~ 20	<5

Table 2: Combustion balance improvement obtained within a few days using soft sensors to correct secondary air distribution (Blondeau, Rijmenans, et al. 2018)

6.2 True local air-fuel ratios

Combining the EUCoalFlow (fuel distribution) and the EUSoft Air (air distribution) systems, the operator gains access to the true air-fuel ratios at the level of the burners, while those values can only be estimated using standard data. Given that the local air-fuel ratio is a predominant factor for the formation of NO_x and for the determination of CO concentration in the burner belt, this information is crucial.

The comparison between the values expected by the operator based on standard measurements and the true values can be quite surprising, as illustrated in Figure 12 for a large-scale coal-fired power plant. In that case, while the burner equivalence ratios predicted by the standard equipment were in the range 0.9−1.05, it was shown that the actual range was significantly broader (0.65−1.25). This is due to the cumulated uncertainties on both air and fuel distribution. The computed global equivalence ratio λ for the lower burner row was ~0.8 instead of the expected value of ~0.9.

6.3 Flame centering

The combination of the EUFlame and the EUSoft Air systems is an efficient way to solve flame centering issues in the furnace, that can cause premature tube failures due to high local heat flux or CO concentrations.

The consequences of the actions taken to balance the secondary air distribution to burners are immediately seen in the control room by monitoring the 2D FEGT field provided by the IR-pyrometers.

Figure 13 illustrates the type of improvement that was achieved in a tangentially-fired boiler presenting air flow imbalances.

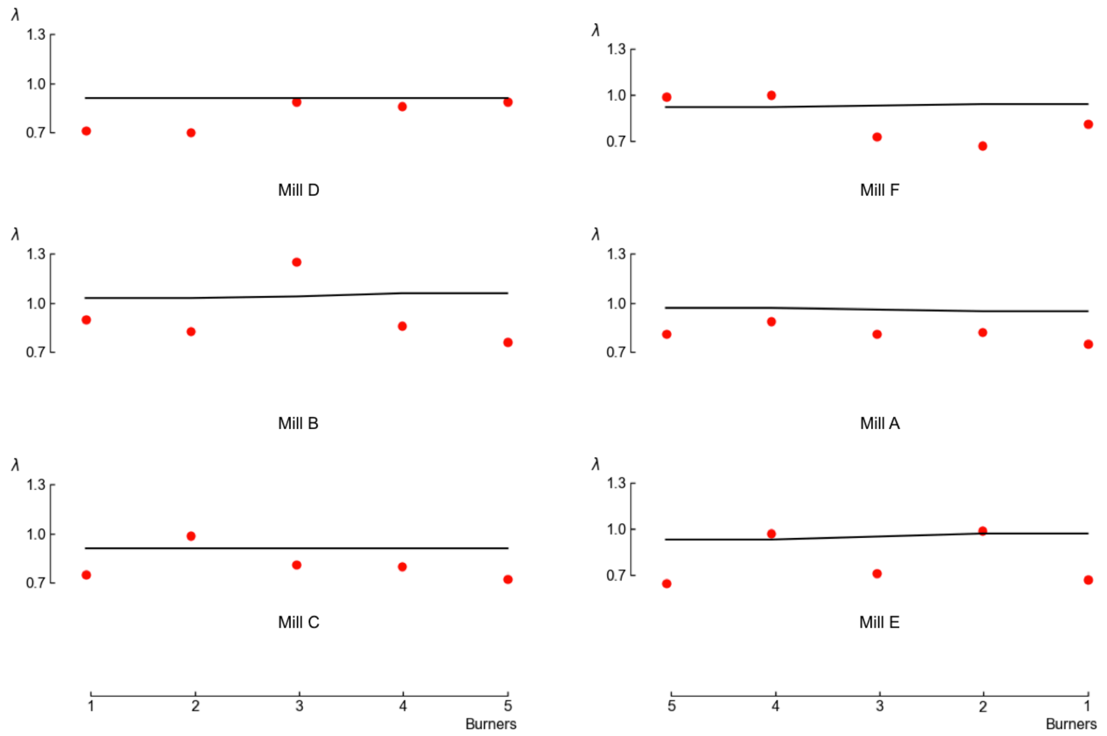

Figure 12: Equivalence ratio at the burner level in a large-scale coal-fired power plants – expected values based on standard equipment (line) vs. true value measured by combining the EUCoalFlow and EUSoft Air systems. The actual range is 0.65-1.25 instead of the expected 0.9-1.05 (Blondeau, Rijmenans, et al. 2018)

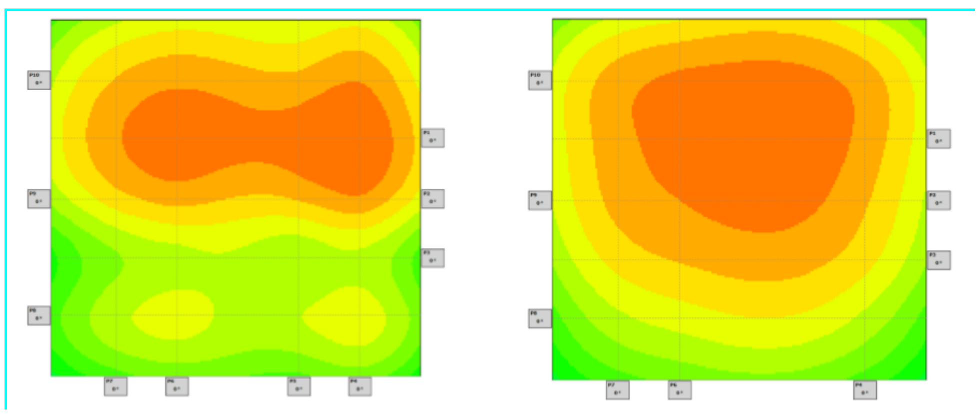

Figure 13: 2D FEGT field before (left) and after (right) improvement of the position of the flame in a tangentially-fired boiler.

6.4 PSD optimisation

As explained in §4, the avoidance of particle sampling and lab analysis for PSD measurement by using a laser probe allows for an immediate and dynamic feedback on any corrective action carried out to optimise the coal particle sizes. Inserting the EUCoalSizer probe in the coal feed lines gives a direct view on the consequences of primary air flow or mill settings modification on PSD.

Figure 14 shows the results of a dynamic test performed in a large coal-fired power plant: the mill classifier speed was modified, and the PSD was measured online. Not surprisingly, the ratio of particles smaller than 75 µm increased with an increasing classifier speed, while the ratio of particles larger than 300 µm was decreasing. Both the 75-150 and 150-300 µm ranges exhibited a decreasing share as well.

The EUCoalFlow system was also used simultaneously to quantify the impact of the classifier speed on the coal distribution to the burners. Figure 15 shows that the distribution is improved for higher classifier speeds, i.e. when smaller coal particles are produced.

It was the first time that such dynamic tests were performed, and this opens the door to regular and easy PSD and coal distribution optimizations.

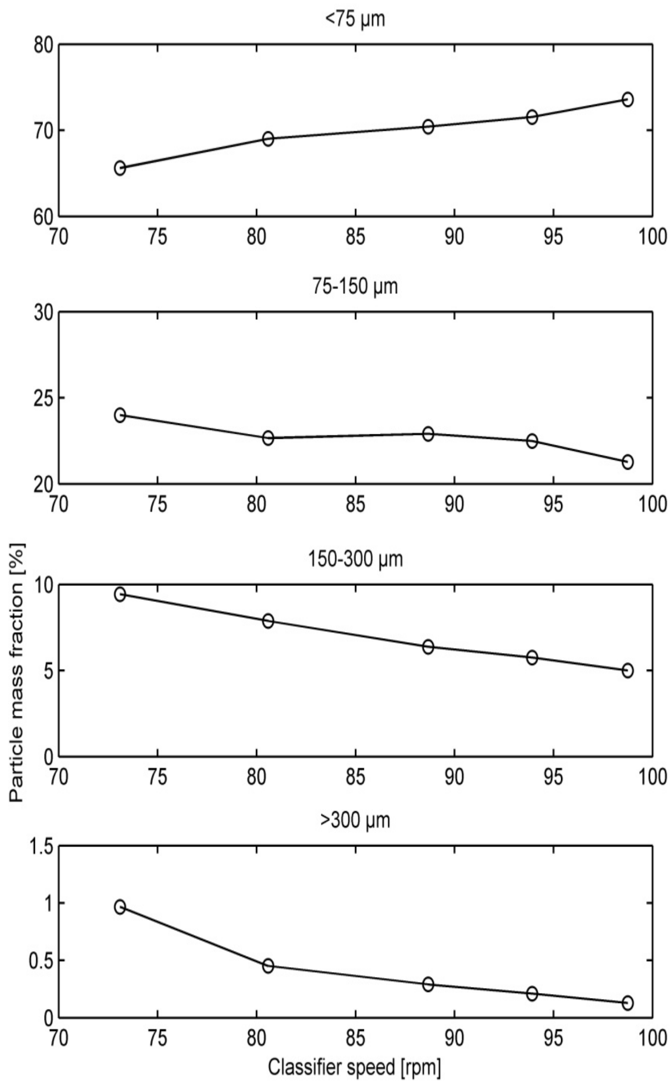

Figure 14: Effect of an increasing mill classifier speed on PSD, as measured with an EUCoalSizer laser probe (Blondeau, Koch, et al. 2016)

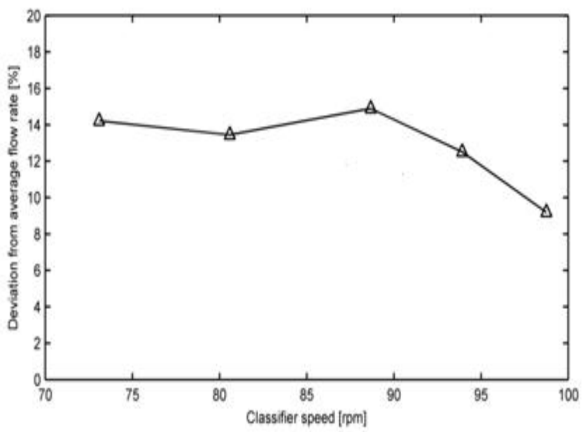

Figure 15: Effect of an increasing mill classifier speed on coal distribution to burners, as measured with the EUCoalFlow microwave sensors (Blondeau, Koch, et al. 2016)

7 Financial impacts

For some of the improvements brought by the use of advanced combustion monitoring tools, a direct positive financial impact can be assessed. In this paragraph, we used known cases to evaluate the financial benefits of representative:

1. Reduced carbon in ash,
2. Optimized boiler derating after a change in the fuel mixture,
3. Reduced evaporator tube failures,

that can be typically achieved using the described tools and metholodogies.

A reduction of the carbon content in ash can be obtained through an optimisation of the fuel Particle Size Distribution and/or the fuel and air distributions. By decreasing the carbon content in bottom ash from a rathe high value of 10% down to an acceptable value of 5%, the total coal consumption of the plant can be decreased with 0.7%. For a 650 MWe power plant running 7800 hours per year (90% availability), the annual saving is approximately 1 MEur. These savings reach 2 MEur for an initial carbon content in bottom ash around 15%.

For boilers burning different types of fuel, the management of slagging and fouling is extremely complex, as ash chemistry is far from being a linear phenomenon. Specific combustion settings can be defined for each type of fuel such that costly outages for unplanned boiler cleaning can be avoided. In a power plant experiencing slagging issues due to a change in the fuel mixture, 3 days of unplanned outage occurring every 2 to 3 months have been avoided by decreasing the power production with 25 MWe. The objective was to decrease the FEGT below the Ash Fusion Temperature (AFT) of the fuel. Such a derating is generally done according to the operators' return of experience, which might lead to a power output limitation that is beyond what is strictly necessary. Using online monitoring of Particle Size Distribution, fuel and air distribution, and FEGT, the operator can constantly look for the optimum operational settings that minimize the production losses. When the average power can be re-increased compared to the initial derating, the annual benefit of the plant is increased with 0.2 MEur per additional MW for a power plant with a 90% availability.

By keeping the flame centered in the furnace, the number of outages due to tube failures can be dramatically reduced. Cases were reported where 1 outage per year was avoided, leading to 1 MEur additional benefit.

8 Conclusions

Combustion in utility boilers is generally not well monitored. A lot of crucial parameters are only estimated, or available after unreasonable delays. The growing demand for fuel- and load-flexibility even further emphasizes the need for accurate, online monitoring of the main combustion parameters in large-scale power plants. Current, standard equipment is not able to provide the operators with the needed control of local air distribution, local fuel distribution, particle fineness and Furnace Exit Gas Temperature for different fuels (or fuel mixtures) at various loads.

Innovative tools are however available on the market to face these challenges. The EUFlame system gives an online, 2D image of the temperature field at the outlet of the furnace, while the EUSoft Air and the EUCoalFlow systems provide an online monitoring of the air and fuel flow rates to the burners, allowing for a better control of the local air-fuel ratios. The EUCoalSizer system gives an instantaneous measure of the Particle Size Distribution without sampling and without lab analysis. Depending on the specific requirements for a given unit, the combination of several of these tools addresses the need to retrieve more information on the combustion process, leading to increased performances and flexibility.

Online flame centering, air distribution tuning, air-fuel ratio correction or Particle Size Distribution optimization were performed at full scale with such equipment, or combinations thereof.

These tools allow the operators to perform both:

1. Corrective actions to tackle specific technical issues
2. Efficient online monitoring for constant process optimisation

Cases were reported for which the positive financial impact of solving well-known combustion issues with the proposed tools can be assessed. Using online monitoring tools in case of typical unburned carbon issues, power derating optimization, and tube failure reduction can lead to savings or additional revenues of 1 MEur/y, providing excellent business cases for the use of advanced combustion monitoring tools.

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