Effective emissions reduction and plant optimization with smart combustion performance analysis

Yusuf Serkan Yavaş[1], Stefan Heidinger[2], Hasan Utku Kilinc[1], Enno Trennert[2], Eike Martensen[2], David Albus[2], Ismail Korkmaz[2], Francesco Turoni[2]

Abstract

A smart combustion performance analysis for thermal power plants can help to evaluate the combustion process and thus derive more effective measures for its control and optimization in a limited amount of time and with minimal manpower. Due to the innovative approach and the temporary application of suitable, modern online diagnostics, together with data analytics, a reduction of CO and NO_x levels, the homogenisation of the furnace exit gas temperature, the matching of fuel and air mass flows at each individual burner, and an overall narrowing of the process parameter spread can be achieved.

This case study illustrates the benefits of the approach in practice, showing the capability and potential of efficiently evaluating the combustion process performance of the Sugözü coal-fired power plant.

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[1] İskenderun Enerji Üretim ve Tic. A.S., Adana, Turkey

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List of abbreviations

AFR	air-fuel ratio	LoI	loss on ignition
CO	carbon monoxide concentration	NO_x	nitric oxide concentration
DCS	distributed control system	O_2	oxygen concentration
FEGT	furnace exit gas temperature	λ	air-fuel equivalence ratio

1 Introduction

ISKEN Sugözü Power Plant (ISKEN) commits itself to operating its coal-fired units in accordance with the highest international technical standards. In order to meet these requirements, reliable, efficient, and environmentally friendly operation with high availability even under difficult changing process conditions is a basic prerequisite.

To fulfil its goals and exploit existing potentials, ISKEN has turned to EUtech to assess and analyse the combustion process in an innovative and efficient manner using online diagnostics and data analytics.

The quality of combustion is strongly influenced by various variables: fuel quality and its preparation, air quantity and distribution, and the resulting air-fuel equivalence ratio (λ) at each individual burner. These parameters influence ignition delay, combustion efficiency, loss on ignition (LoI), fouling, and, above all, emission levels. Moreover, the wear and tear of pulverisers can cause severe degradation of fuel conditioning over time.

The furnace exit gas temperature (FEGT) and its distribution over the boiler cross-section are the key factors for thoroughly evaluating the combustion process, and their visualization enables the minimization of pollutant emissions through primary and secondary engineering measures. With suitable, modern online diagnostic systems, these variables (fuel distribution, air distribution, and temperature distribution) can be measured simultaneously, and the data can be utilized to identify problem root causes and optimize the combustion and gas cleaning processes.

First, the combustion process is analysed by examining historical data from the power plant's existing sensors, as outlined in **Section 2**. As a result of this preliminary investigation, hypotheses are derived as to which parts of the combustion process have potential and how these can be addressed in **Section 3**. Subsequently, a targeted measurement campaign is designed to test these hypotheses using suitable EUtech sensor technology (**Section 4**).

After identifying exiting inefficiencies, the optimization of the combustion process and a direct comparison of characteristic quantities of the combustion process before and after the intervention are presented in **Section 5**. Finally, the findings of the work are summarized in **Section 6,** and an outlook is given in **Section 7**.

2 Preliminary analysis – status quo

2.1 Theoretical background and general plant data

An example scheme, similar to the investigated unit at the Sugözü coal-fired power plant, is displayed in **Figure 1**. Feeders feed the raw coal into four mills, where the coal chunks are pulverized. A classifier retains the coarse particles, while the fine particles are dragged along with the primary air to the different burners in the furnace. The coal is then burned in the furnace with the help of additional air at different stages (i.e., secondary, tertiary, and over-fire air) in order to reduce the emission of NO_x and CO.

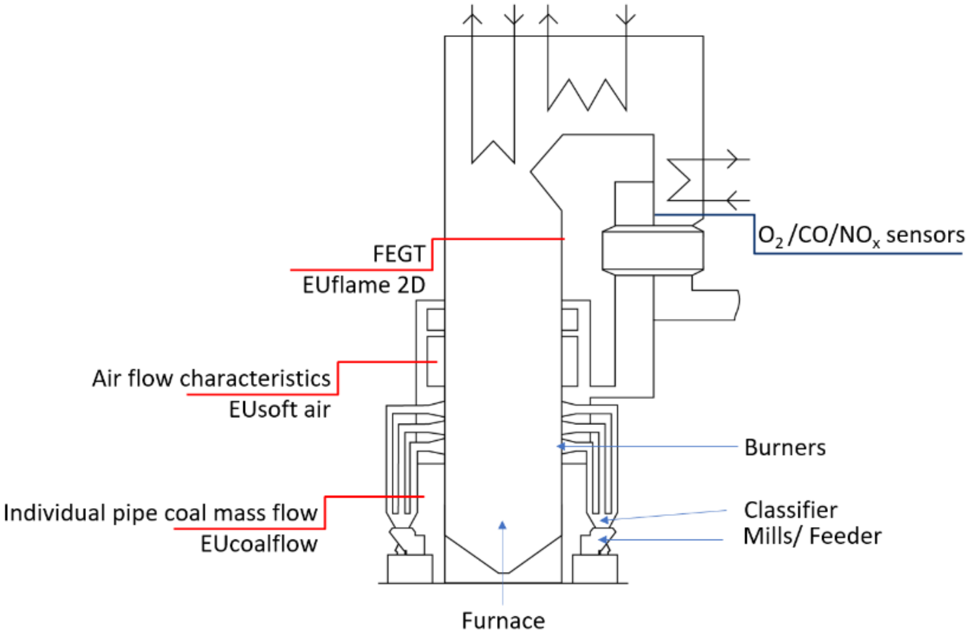

***Figure 1**: Schematic of the boiler with main components and the approximate position of the referenced sensors.*

Besides the operational data of the plant unit, the degrees of freedom that can be utilized for optimisation need to be explored. With no actuators (e.g., coal valves) in the individual coal pipes, the pipe-to-pipe fuel flow can only be minimally influenced by operating the mills differently (e.g., with different feeder loads). Nevertheless, several dampers exist in the airways. These actuators can be adjusted online, during operation, in the distributed control system (DCS). Additionally, manual air dampers (i.e., secondary and tertiary swirlers) are also available and can be adjusted manually to get a better flame shape and combustion; however, they are usually not changed during operation due to a lack of adequate sensorics. The secondary air dampers for the front and rear burner rows are automatically controlled based on the calculated λ values per side. [1]

The data sets analysed hereafter reflect a ten (10) day time frame with various load changes. The profile of the electrical load is plotted in **Figure 2** to convey phases of full load and lower load for better interpreting the following data. This is important in order to differentiate between changes in quantities due to load changes and those due to other effects.

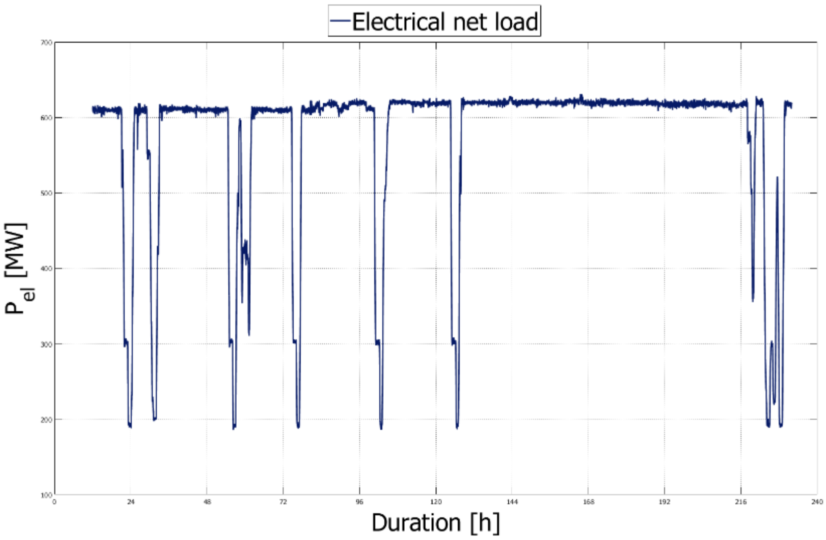

***Figure 2**: Electrical load profile.*

2.2 Exhaust gas composition

The carbon monoxide concentration (CO) and the combined concentration of nitrogen oxide and nitrogen dioxide (nitric oxide - NO_x), both measured before the selective catalytic reduction (SCR) unit, were analysed along with the excess oxygen concentration (O_2). The fractions of these exhaust gas components are plotted in **Figure 3**. The O_2 concentration is measured over the cross-section of the exhaust gas stream with three separate sensors. Besides the significant amount of excess oxygen occurring temporarily in lower load phases in all three signals, a substantial deviation between the sensors can also be seen in **Figure 3a**, implying an uneven O_2 distribution during combustion in the furnace.

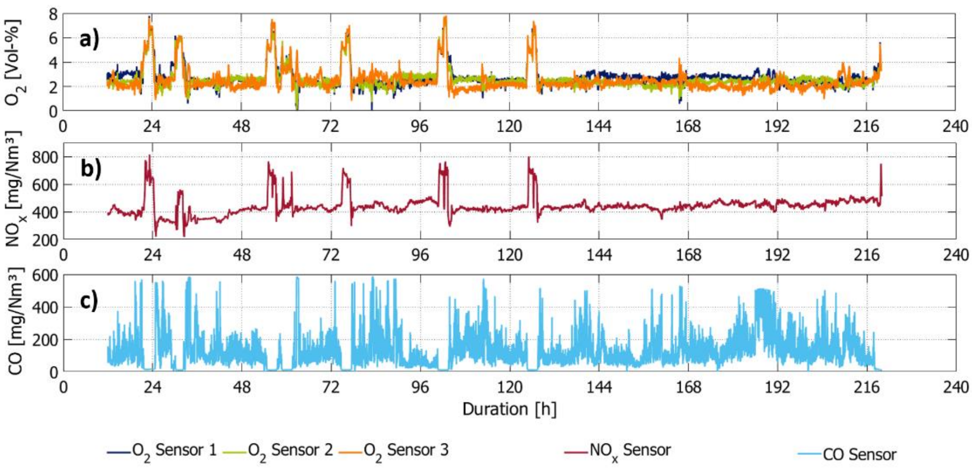

***Figure 3**: Selected exhaust gas components. **a)** oxygen concentration sampled in the exhaust gas stream before the SCR via three probes distributed over the cross-section. **b)** nitric oxide concentration sampled before the SCR. **c)** carbon monoxide concentration sampled before the SCR.*

The mass flow of the combustion air can be set in relation to the fuel mass flow, calculating the air-fuel ratio (AFR = $\dot{m}_{air}/\dot{m}_{fuel}$) [2]. Thereupon, by setting the amount of oxygen theoretically necessary to oxidize the entire fuel in relation to the oxygen content in standard air, the air-fuel equivalence ratio (λ = AFR/AFR_{stoich}) can be calculated. The NO_x and CO levels are directly tied to the O_2 levels, depending on how much oxygen is available for oxidation [3]. On the one hand, too much excess oxygen results in high NO_x

concentrations and a reduced thermal efficiency of the combustion. On the other hand, the low CO levels that occur in this configuration are desirable [4]. This trend behaves vice versa for too little excess oxygen, while additionally, loss on ignition (LoI) starts to occur. The laid-out optimization problem is sketched qualitatively in **Figure 4**. These dependencies are also reflected in the data, where the CO (**Figure 3b**) and NO_X (**Figure 3c**) concentrations match the excess O_2 concentrations in the derived manner.

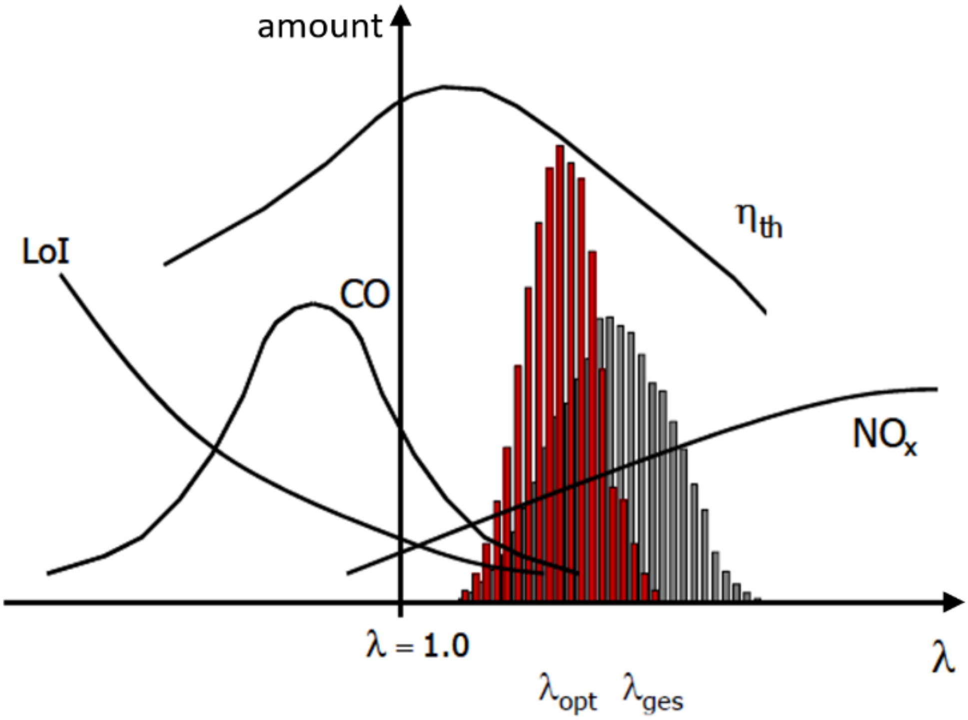

***Figure 4**: Qualitative plot of the effects of various air equivalence ratio degrees during combustion.*

2.3 Fuel mass flow

The fuel mass flow from the four coal feeders is the last preliminary data set that was analysed beforehand. As with the previous data sets, the times of lower loads are easily recognisable with some of the mills switched off, resulting in a zero mass flow. Besides the mass flow fluctuations occurring in all four mills, the material throughput decreases along the vertical development of the furnace. Thus, the burners lower in the furnace and, therefore, with longer fuel residence time in the boiler, are loaded more.

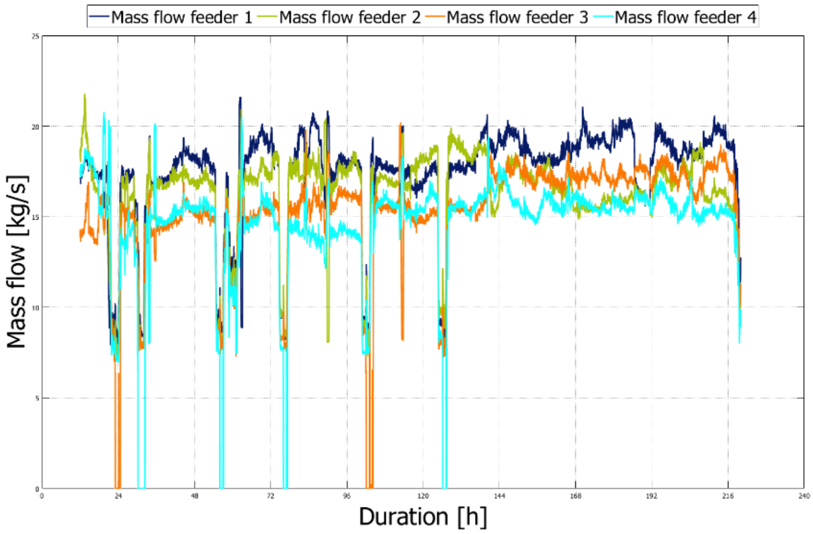

Figure 5: Feeder load profiles of the four mills, with feeder 1 supplying the lowest burner level and feeder 4 supplying the highest burner level.

Different types of imported coal are used in the plant, while in recent times, small amounts of local coal (< 10%) have also been blended. This adds another dynamic to combustion behaviour, necessitating the need for improved combustion hygiene.

3 Hypotheses

The most striking features of the data sets provided can be summarized as significantly fluctuating CO values with an unevenly distributed oxygen concentration and fluctuating superheater steam temperature. The staging of fuel and air inputs (primary and secondary) appears to be an area with optimization potential as well. The combination of these findings indicates inhomogeneous combustion in the furnace. Utilizing the results from the preliminary analysis, the following hypotheses for the causes of the mentioned challenges can be derived.

The two most likely reasons for an inhomogeneous combustion in the furnace are an imbalance of the fuel injection and/or the air injection [2]. Therefore, the most obvious hypotheses are:

> Hypothesis 1: The coal pipe-to-pipe distribution is unequal at one or more of the mills in operation.
>
> *Hypothesis 2:* Suboptimal air distribution causes local under- and over-stochiometric air conditions and thus suboptimal emission levels (e.g., fluctuating CO).

In case one or both of Hypotheses 1 and 2 are true, an inhomogeneous FEGT distribution over the furnace cross-section would be the direct result.

> *Hypothesis 3:* The FEGT distribution over the furnace cross-section is inhomogeneous.

Additionally, to diagnose the issues, it is vital to identify possible paths for mitigating the problems and improving combustion hygiene. If Hypotheses 1 and 2 are correct, the local mismatch between fuel and air supply leads to an unevenly distributed FEGT over the furnace cross-section, as suspected in Hypothesis 3. This further implies that some of the fuel is burned in an O_2-rich environment and some of the fuel is burned in an O_2-lean environment. While the first case would result in elevated NO_x levels, the latter case would result in elevated CO levels, as derived in **Section 2.2** and sketched out in **Figure 4**. Mitigating the causes, postulated in Hypotheses 1 and 2 would result in a reduction of undesirable emissions [3].

> *<u>Hypothesis 4:</u>* With adjustments in the air path, the combustion can be improved and thus the emissions reduced, with an emphasis on the reduction of CO emissions.

Apart from the coal quality, temperature level and distribution have a significant impact on fouling and slagging in the furnace. Fouling caused by localised high temperatures decreases the heat transfer rate and thereby reduces the thermal efficiency. With improved combustion hygiene and, thus, FEGT level and distribution, slagging and fouling issues can be reduced [5].

4 Measurements

In order to test the formulated hypotheses, a measurement program is designed to gain insights into the actual combustion process without interfering too much with the daily boiler operation. To limit influencing factors and enhance reproducibility, the boiler operation was carried out at different loads with specific mill constellations and specific mill loads, but otherwise the boiler was in normal operation using the usual coal.

4.1 Hypothesis 1 - The coal pipe-to-pipe distribution is unequal in one or more of the mills in operation.

The measurement and analysis of the coal flow distribution in each pipe are necessary for an accurate, reliable, and local λ calculation. Different systems can be used for this purpose, but typically they detect the coal distribution only at one instance in time and at one mill operation point. Because the coal flow distribution can vary depending on mill load, coal quality, water content, air flow, and mill wear conditions, these classical measurements are suboptimal. Therefore, an accurate and continuous online coal flow measurement at all the pipes of one mill is required. The coal distribution is measured using a portable coal flow measuring system (EUcoalflow) to measure the flow simultaneously in all six burner lines behind each mill [6]. Thus, imbalances, deviations during load changes, and fluctuations can be identified. During the measurement period, each mill is analysed in sequence. EUcoalflow is designed for dynamic coal flow balancing and control. It is based on non-intrusive micro-wave sensors that continuously measure the mass flow and velocity of coal inside coal pipes and quantify the imbalance of coal flow from pipe to pipe. **Figure 6** shows the typical application of the EUcoalflow sensors at the coal pipes. Three sensors are positioned 120 ° apart on one level.

Figure 6: *EUcoalflow system in a power plant, measuring the fuel mass flow in each individual coal pipe.*

4.2 Hypothesis 2 - Suboptimal air distribution causes local under- and over-stochiometric air conditions and thus suboptimal emission levels.

Considering that the investigated boiler does not have individual air flow measurements per burner, a model-based strategy for calculating local air flows is applied to obtain a detailed picture of the combustion air distribution in the furnace. The air flow distribution and thus the air-fuel equivalence ratio (λ) are derived by using a model-based system (EUsoft air) on the pneumatic structure of the complete air path [7]. The basic principle is to take advantage of the most reliable physical measurements available to reconstruct the complete air distribution. The boiler hydraulic network model is trained based on historical data (e.g., pressure measurements, damper openings, total air flows, excess O_2, etc.) and structural information of the hydraulic network, as highlighted in **Figure 7**.

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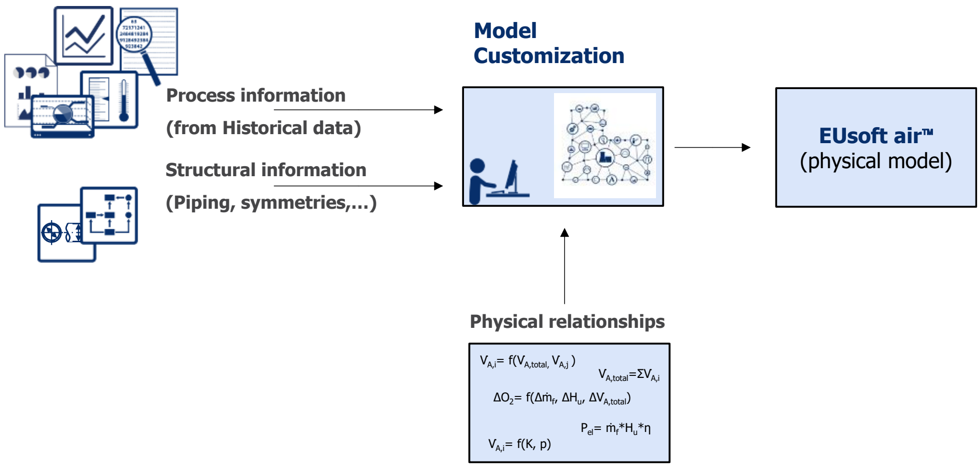

***Figure 7**: EUsoft air – approach and methodology.*

4.3 Hypothesis 3 - The FEGT distribution over the furnace cross-section is inhomogeneous.

The two-dimensional FEGT level and distribution are measured via a portable measuring system based on optical pyrometers (EUflame 2D) [8]. The EUflame 2D system with eight sensors is used to measure the flue gas temperatures at the end of the furnace inside the boiler and to calculate the temperature distribution. Through the EUflame software, six main FEGT temperature zones were defined and used for combustion analysis, as shown in **Figure 8**.

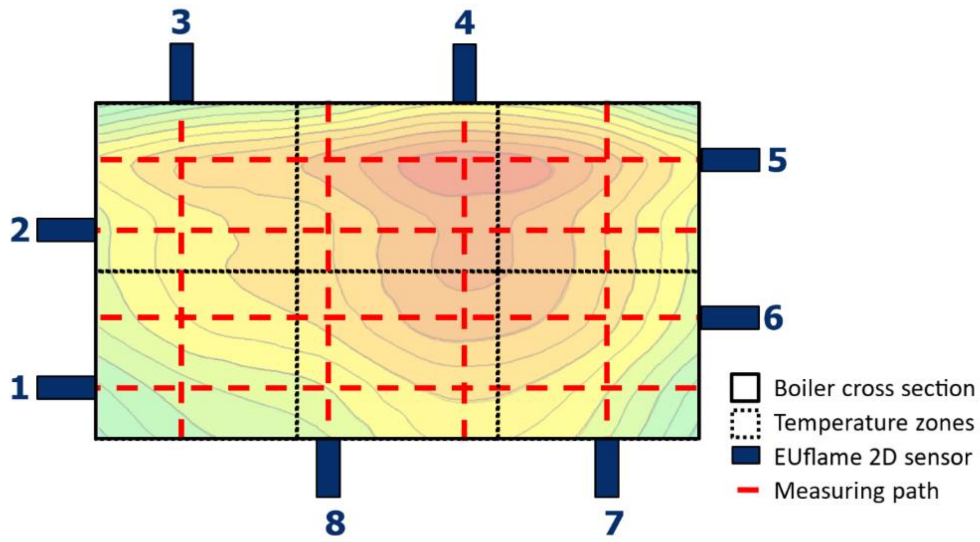

Figure 8: Sensor setup for the EUflame 2D system with defined temperature zones.

5 Results & Optimization

5.1 Hypothesis 1 - The coal pipe-to-pipe distribution is unequal at one or more of the mills in operation.

Three of the four mills showed no noteworthy mass flow imbalance between the feeding pipes of less than 10%. One mill showed a notable mass flow imbalance of up to 25% in the adjacent pipes, as displayed in **Figure 9a**.

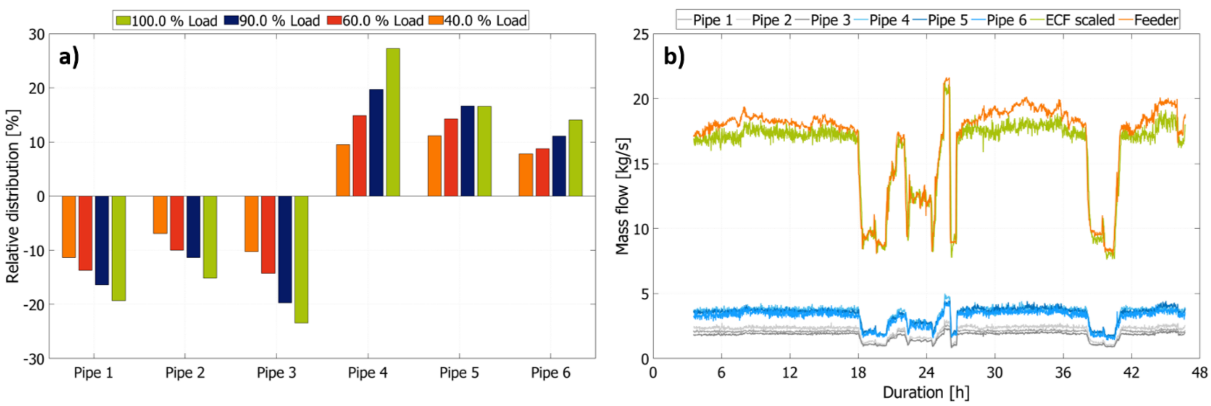

***Figure 9**: Mass flow at one of the mills for each individual pipe 1-6 at various loads. **a)** relative mean mass flow distribution. **b)** plot of the individual coal mass flows as well as the aggregate of the pipes and the signal from the feeder over time.*

While pipes 1-3 of the investigated mill supply the burners in the front of the furnace, pipes 4-6 supply the burners in the rear. This means that the burners in the front are consistently supplied with less coal than the burners in the rear. This effect is less pronounced for lower loads, and it is also notable in **Figure 9b**, where the sum of the six signals from the individual pipes matches the signal from the feeder well. This is also true for the dynamic behaviour when the feeder flow or the classifier speed changes.

<u>The first hypothesis is confirmed by one of the mills supplying an imbalanced fuel mass flow to the front burners compared with the rear burners.</u>

Considering that there is no direct possibility to adjust the coal distribution, the focus of the adjustments is on the air paths. The analysis of possible adjustments revealed that there are some possibilities to adjust the secondary air distribution if the local λ values are available. Additionally, the analysis of the excess oxygen at low loads shows that, in general, enough air is going into the boiler; however, most likely the air is not distributed optimally.

5.2 Hypothesis 2 - Suboptimal air distribution causes local under- and over-stochiometric air conditions and thus suboptimal emission levels.

The boiler is equipped with secondary air flow measurements for each burner group (3 burners in the front or three burners in the rear), while assuming an equal distribution between the individual burners. The air flow for each individual burner is determined with the EUsoft air system. In conjunction with the fuel mass flow to each burner determined by the EUcoalflow, the λ for each individual burner can be calculated. The λ values for all burners over time are displayed in **Figure 10**. Some of the burners are operated with a suboptimal low or suboptimal high λ.

<u>Hypothesis 2 is confirmed by the derived suboptimal low and suboptimal high λ values at some of the burners.</u>

Generalized over all burners, the λ could be narrowed by adapting the various dampers in the airway. Additionally, the coal mass flow imbalance between the front and rear burner groups that was pointed out in the previous section could be partially compensated with the adaptation of the secondary air. The secondary air was decreased in the front and increased in the rear in order to homogenize the combustion. The frequency of O_2 lean and O_2 rich events, as well as the spread of occurring λ values, could be significantly reduced, as displayed in **Figure 10**.

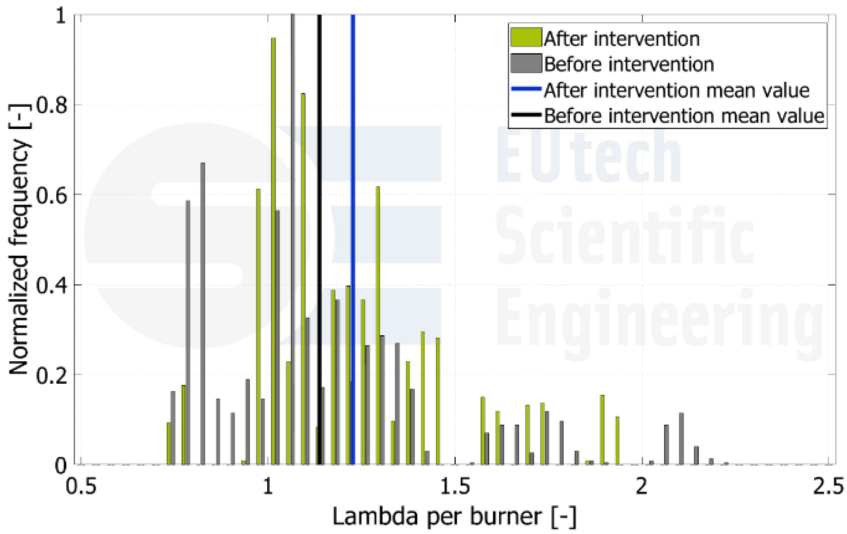

***Figure 10**: λ values at the individual burners, calculated with the mass flow measured by EUcoalflow and the air flow measured by EUsoft air before and after the optimization.*

5.3 Hypothesis 3 - The FEGT distribution over the furnace cross-section is inhomogeneous.

The positive effect of tuning the secondary air supply with the help of EUsoft air is well conveyed by the FEGT distribution visualised via the EUflame 2D, as displayed in **Figure 11**. Several positive results could be achieved. The hottest spot in the furnace cross-section used to be close to the rear left corner and is now moved towards the centre of the furnace, reducing the risk of thermal stresses and corrosion at the boiler walls. Additionally, the highest temperature could be reduced by approximately 60 K, while the minimum temperature stayed the same, implying an overall homogenisation of the temperature distribution, leading to better heat transfer and overall process behaviour [9] [10].

Hence, hypothesis 3 has been confirmed, and a significant improvement was achieved.

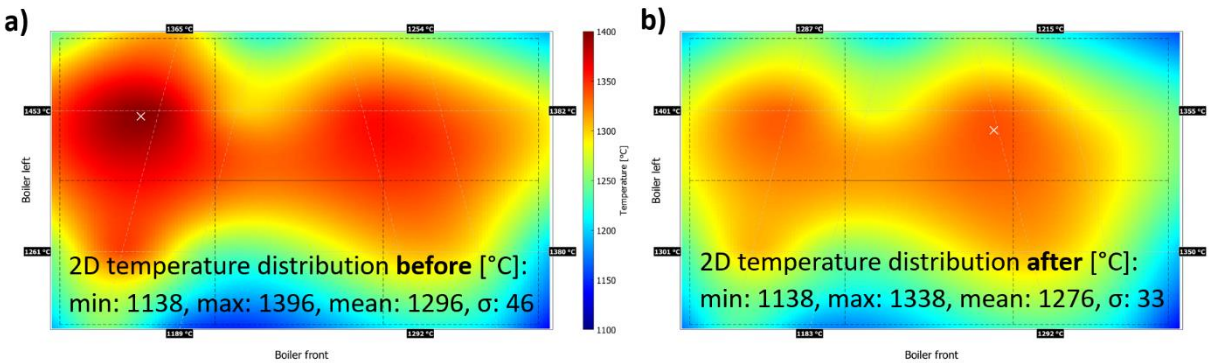

Figure 11: *Furnace exit gas temperature measured and visualized by the EUflame 2D system. The white cross indicates the spot with the highest temperature.* ***a)*** *Before the intervention;* ***b)*** *after the intervention.*

5.4 Hypothesis 4 - With adjustments in the air path, the combustion can be improved and thus the emissions reduced, with an emphasis on the reduction of CO emissions.

The mass flow imbalance between the rear and front burners was pointed out in **Section 5.1** and was successfully compensated with the secondary air supply, as explained in **Section 5.2**. This resulted in a more homogeneous FEGT distribution, as demonstrated in **Section 5.3**. Tuning the air mass flow to the fuel mass flow for each part of the furnace locally creates the desired λ, and therefore reduces the production of NO_x and CO, respectively, as laid out in **Section 5.4**. This is also reflected in the CO levels before and after the intervention, as displayed in **Figure 12a**. Here, two significant effects are observable. On the one hand, the CO levels were reduced in general, moving the average towards lower CO values. On the other hand, the distribution was narrowed, implying improved process control. These two combined effects lead to a significant reduction in CO limit violations. The NO_x levels are displayed in **Figure 12b** before and after the intervention. Even though the mean NO_x levels are increased, the spread is significantly reduced, leading to fewer limit violations due to better process control. This is also reflected in the use of ammonia, which is reduced by approx. 30% after the optimization, as can be derived from **Figure 12c**. Ammonia injections are utilized as a countermeasure in order to oxide NO_x and guarantee below-limit NO_x emissions. Overall, CO and NO_x level limit violations are significantly reduced by EUtech's intervention.

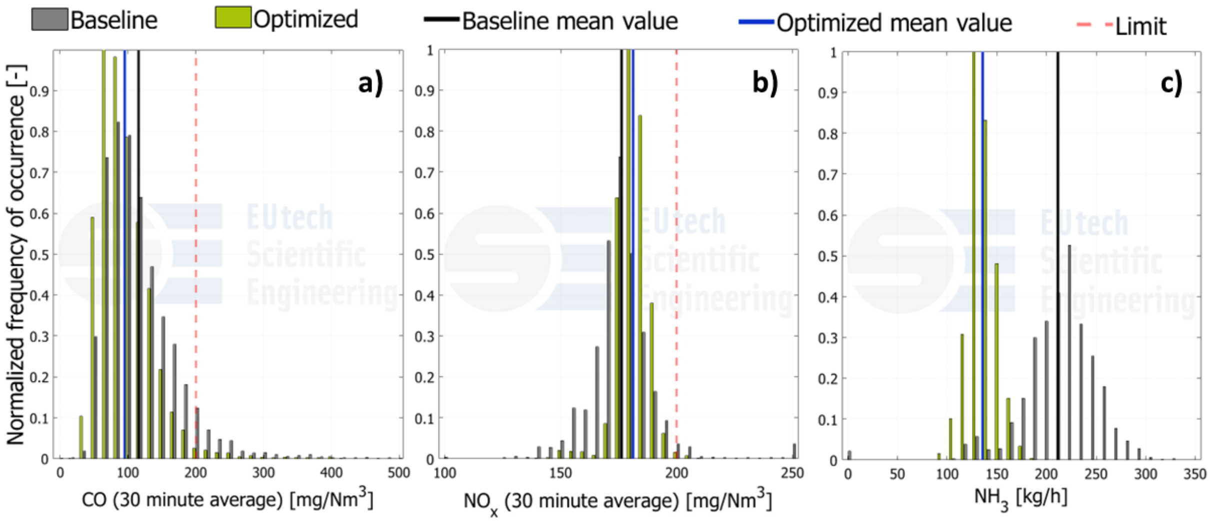

***Figure 12**: Frequency of occurrence of exhaust gas component fractions before and after the optimization. a) carbon monoxide; b) nitric oxide; c) amount of used ammonia.*

6 Summary and Conclusion

EUtech assessed the combustion process in the Sugözü coal power plant in full operation regarding fuel and air flows, air fuel equivalence ratio, furnace exit gas temperature, as well as O_2, CO, and NO_x levels. This was achieved with a combination of EUtech's measurement systems for fuel mass flow at each single burner (EUcoalflow), two-dimensional gas temperature distribution (EUflame 2D), and a virtual sensor application for the air fuel equivalence ratio (EUsoft air), along with the plant's own sensors. The unit is generally operated well. Nevertheless, by tuning the staging of secondary air to the specific fuel mass flow at each burner, the following beneficial effects were achieved:

- The furnace exit gas temperature was significantly homogenised over the entire cross section of the boiler.
- The air fuel equivalence ratio for each burner was narrowed to the intended level.
- The CO emissions were reduced substantially.
- The NO_x limit violations before ammonia injection were reduced substantially.
- The amount of used ammonia was reduced by about 30%.
- The overall variance of process parameters was reduced.

Through EUtech's intervention, the combustion process in the power plant was efficiently analysed and improved, while reducing emission levels and slightly increasing the overall power plant efficiency.

7 Outlook

In light of the results of the combustion performance evaluation and the interventions carried out together with EUtech during the measurement campaign, the Sugözü coal power plant will install permanent systems for online determination of all airflows for each individual burner of both boilers.

This, together with the use of the EUcoalflow system, allows automatic adjustments of the combustion process based on actual load conditions, fuel composition, mill wear, etc. Therefore, the observed benefits and associated improvements in availability will be achieved and maintained reliably and efficiently well into the future.

8 References

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