Enhancing combustion-driven boiler efficiency and competitiveness through advanced two-dimensional temperature measurement using optical pyrometers

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Abstract

This article presents the successful application of a smart two-dimensional temperature measurement system based on optical pyrometers for real-time determination of the two-dimensional flue gas temperature distribution at the end of the furnace (FEGT) in combustion-driven boilers. The study revolves around the optimization results achieved at EREN Enerji - ZETES II, where an advanced measurement system based on contactless optical sensors (EUtech EUflame 2D™) was applied to a 615 MWel wall-fired boiler.

The implemented 2D temperature measurement system has demonstrated its effectiveness in adjusting and thus homogenizing the temperature distribution within the boiler cross-section. With the help of the continuous tomographic reconstruction of the temperature distribution at the furnace outlet, inhomogeneities due to suboptimal burner air-fuel-ratios (AFRs), for example, can be easily detected, identified, and corrected. The achieved homogenization not only serves to optimize the combustion process but in turn enables a significant reduction in excess oxygen, leading to a notable improvement in boiler efficiency across various load ranges. Additionally, the power plant is operated with blends of Russian coal, Colombian coal, and local coal with different properties. This adds another dynamic to the combustion process and by following the FEGT, operators are reducing the negative effect of varying coal parameters on the combustion process. This flexibility is crucial in many electricity markets where coal-fired boilers compete in a landscape increasingly impacted by renewable energy sources.

The case study highlights the economic viability and practical benefits of the EUflame 2D system, enabling the customer to enhance the safety, reliability, and efficiency of their boilers from the outset. By minimizing excess oxygen requirements and improving efficiency, the system contributes significantly to the reduction in NO_x and CO emissions, in line with environmental sustainability goals. Notably, the presented state-of-the-art two-dimensional temperature measurement system is applicable to a wide range of thermal processes (e.g. coal-fired, gas-fired, biomass, waste-to-energy plants, etc.). It provides operators with a valuable tool to enhance the flexibility, reliability, and availability of their boilers, thereby minimizing emissions and optimizing performance in the competitive market environment. As fossil-fired power plants continue to navigate the evolving energy landscape, the adoption of advanced and cost-efficient measurement systems become the imperative for maintaining competitiveness and sustainability.

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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

Since 2009, Eren Enerji provides for the rapidly increasing demand of electricity in Turkey's energy sector. The ZETES initiative includes five (5) thermal power units with a total installed capacity of 2.79 GWe located in Çatalağzı and Muslu in the province of Zonguldak. ZETES is composed of a 160 MWe unit with fluidized bed technology, 2x615 MWe units with super critical pulverized coal, and 2x700

MWe units. ZETES II refers to the 2x615 MWe units located in the southern section of the Zonguldak Eren thermal power plant.

Eren Enerji strives continuously for the improvement of the combustion process and overall plant efficiency. After years of controlling and optimizing the combustion process at the two ZETES II units, additional process information was necessary in order to exceed the state of optimization. The key quantity in any combustion driven power plant (CDPP) is temperature. In this regard, a measurement system for the two-dimensional temperature distribution of the flue gas at the furnace exit (FEGT) was considered. After investigating the available options, it was decided for the EUflame 2D system by EUtech with optical pyrometers over alternative systems. The system was installed in March 2023, while within a day after installation, significant improvements to the combustion process could be achieved in terms of flexibility and emissions. In the following, it is highlighted how the flue gas temperature is influenced by various phenomena and how in return various phenomena can be monitored and diagnosed by measuring the FEGT in absolute terms and distribution. Additionally, the case study of ZETES II unit 3 is presented with the immediate optimization of the thermal process enabled by the extra information of the EUflame 2D system. At last, an outlook on how the optimization journey with EUtech continues is provided.

2 Theoretical background

2.1 Temperature related phenomena in combustion-driven power plants

Many phenomena in a CDPP influence - or are influenced - by temperature, while some of them are displayed in Figure 1 and discussed in the following:

2.1.1 Fuel quality variation

All CDPPs are subject to fuel quality variation. While some of them might not be significant (e.g. gas power plants), many of them are. This can be by design, such as waste-to-energy (WTE) power plants or for example when a power plant is operated with blends of coal. The variating heating value of the fuel is directly reflected in the furnace gas temperature for constant fuel mass flow.

2.1.2 Load

Changes in load are reflected in a change in furnace gas temperature. Depending on the kind of fuel supply, the load is controlled by a reduction in overall fuel flow (gas and WTE plants) or by a decrease of local fuel flow (coal/lignite and biomass plants), which in the latter case inevitable leads to a more inhomogeneous temperature in the furnace, since only some burners are affected.

2.1.3 SNCR operation and NH_3 slip

Many power plants rely on the selective non catalytic reaction with the injection of ammonia (NH_3) in order to reduce the emission of nitric oxides (NO_x). The underlying reactions require a temperature window of around 850-1050°C. Missing this temperature window leads either to burning of the ammonia (>1050°C) or to increased ammonia slip, where the NH_3 is emitted into the environment, adding to the emissions described in Section 2.1.6 [1].

2.1.4 High temperature corrosion

Fuel may occasionally contain vanadium compounds or sulphates, which have the potential to create low melting point substances when burned. These molten liquid salts can be highly corrosive to stainless steel and other alloys that are typically resistant to corrosion at elevated temperatures [2].

2.1.5 Fouling & slagging

Residues from the combustion, soot and molten ashes are depositing on the surfaces in the boiler, most importantly on the functional heat transfer surfaces. This phenomenon requires cleaning (e.g. soot blowing [3]), which is cumbersome and costly. Crossing the melting temperature of the ash increases slagging significantly [4] [5].

2.1.6 Emission levels

Carbon monoxide (CO) and NO_x are the most prevalent components in the exhaust gas necessitating monitoring and controlling. The forming of both products is highly temperature dependent [6]. Merely the level of excess oxygen has a greater influence on the forming of these compounds. The interplay of CO, NO_x, and O_2 is highlighted more detailed in Section

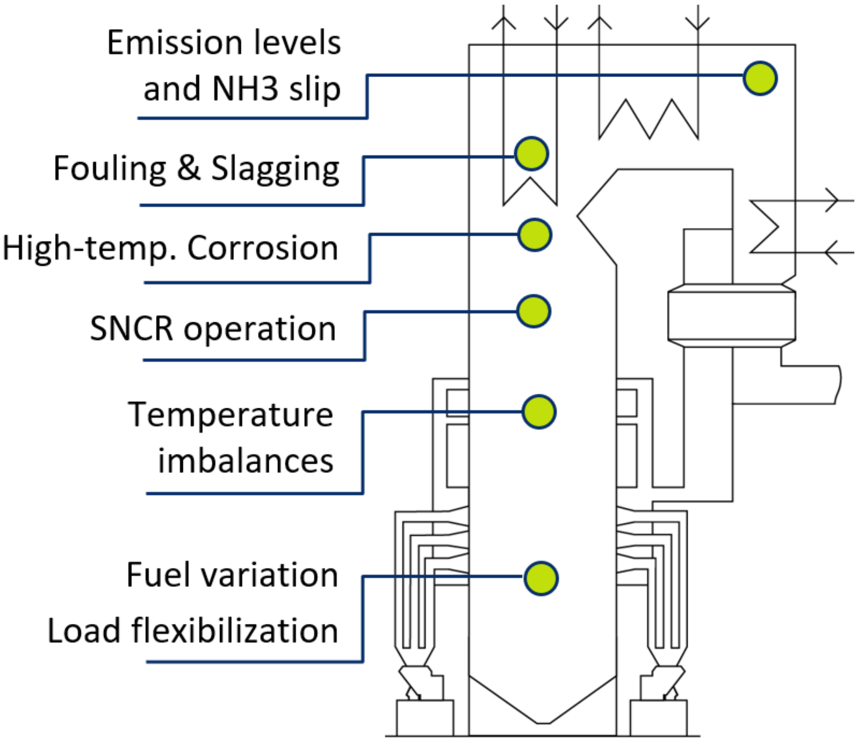

Figure 1: Various areas of the combustion process influencing gas temperature - or influenced by gas temperature.

2.2 Combustion hygiene

Combustion hygiene describes the proper distribution of fuel and combustion air, specifically their locally tuned relation to each other, in order to ensure a ‘clean’ combustion. The relationship between the mass flow of combustion air and fuel mass flow can be expressed by the air-fuel ratio (AFR = $\dot{m}_{air}/\dot{m}_{fuel}$) [7]. This ratio can then be used to calculate the air-fuel equivalence ratio (λ = AFR/AFR_{stoich}) by comparing the amount of oxygen needed for complete fuel oxidation to the oxygen content in standard air. The levels of NO_x and CO are directly influenced by the oxygen levels, which impact the efficiency and emissions of the combustion [6]. On the one hand, excess oxygen can lead to high NO_x concentrations and reduced thermal efficiency, but lower CO levels. On the other hand, insufficient oxygen can result in loss on ignition and elevated CO levels, while the NO_x emissions are reduced. This optimization problem is illustrated qualitatively in Figure 2. These relations hold for the combustion process as a whole but are also important on a local level, e.g. for each burner. At the burners, when the gas temperature is high, often a low λ is favored in order to prevent the forming of thermal NO_x as described in Section 2.1.6. This means moving locally towards low λ-values on the diagram in Figure 2, implying an increase in the CO levels. But since CO is not as stable as NO_x, it can be mitigated by adding more air (oxygen) at later stages of the combustion, when the temperature dropped significantly (over fire air - OFA). This method of emission mitigation via air distribution is called air staging and is part of any good combustion hygiene [8] [9] [10].

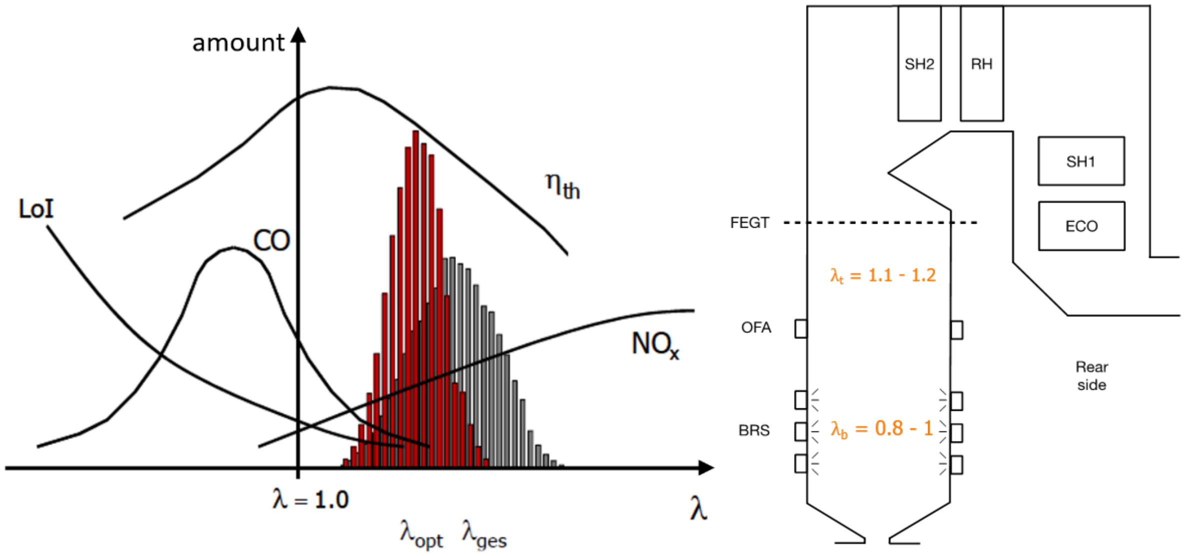

Figure 2 - left: Qualitative plot of the effects of various degrees of the air equivalence ratio λ during combustion. **right**: Common λ-values for air staging in a coal-fired power plant.

2.3 Furnace exit gas temperature as a diagnostic tool

While there are many different temperatures with many different diagnostic meanings in a CDPP, as laid out in Section 2.1, the furnace exit gas temperature (FEGT) allows inferring the quality of the combustion process in the most general way. Knowledge of the FEGT in absolute values and distribution provides indication of:

Absolute temperature level

A quantitative information about the energy content of the flue gas, before entering the superheater.

Temperature balance

A quantitative information of the temperature distribution over the furnace cross-section, visualizing any imbalance, possibly affecting superheater temperature balance downstream.

Hot spot detection

Determining the spot with the hottest flue gas at the furnace cross section is important to assure that no excessive hot gas is close to any surfaces, causing unnecessary thermal stresses and high temperature corrosion issues, as described in Section 2.1.4. Ideally, the highest temperature in the gas should still be lower than the melting point of the ash, in order to prevent excessive slagging, as described in Section 2.1.5.

Qualitative λ at the individual burner

A well-tuned λ at a given burner leads to an optimal combustion and gas temperature. In case the λ is too low, not enough oxygen for the combustion of all the fuel is provided, leading to a lower than optimal temperature. On the opposite, when the λ is too high, each unit of fuel releases its energy into more than the necessary amount of air, leading to a lower than optimal gas temperature as well. This dependency is also reflected in Figure 2. Consequently, spots of low temperatures imply a locally suboptimal combustion hygiene at the respective burners.

Partial load effects

The temporary shutdown of mills for partial load effects the temperature distribution in a certain and often reoccurring manner. The FEGT distribution helps to assess how operating the boiler outside of the point of design affects the process.

Dynamic effects

The visualization of dynamic temperature effects during start-up, shut down and load changes provides valuable information about the state of the thermal process, e.g. real-time temperature distribution.

3 EUflame 2D system

After highlighting the diagnostic power of the FEGT distribution in Section 2.3, a state-of-the-art and cost-effective way for determining this quantity is presented in form of the EUflame 2D system [11]. This measurement system is based on optical pyrometers, which are applied on the outside of the boiler near the end of the furnace, as shown on the left side of Figure 3. Tubing welded to the membrane walls allows for sealed access to the combustion chamber. In most cases, the access holes can be so small that they fit on the fin between membrane tubes with no need for tube bending on boiler walls.

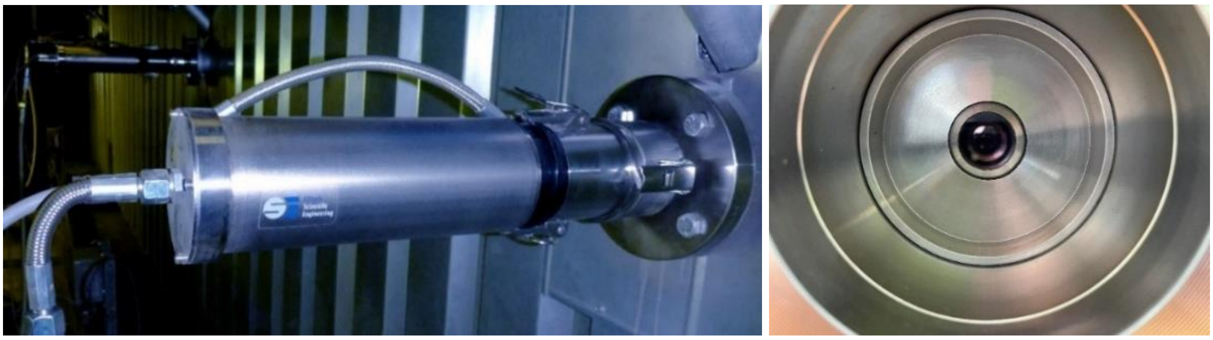

Figure 3: EUflame sensor. **left**: mounted at boiler wall with cooling jacket; **right** temperature resistant sapphire glass in the center, protecting the sensor behind; view from the boiler.

The sensors are supplied with pressurized air and a low but constant air stream over the glass protects the sensor from depositing fly ash, as shown on the right side of Figure 3. For high temperature boiler environments, the sensor can be additionally equipped with a cooling jacket. For applications with excessive combustion residues in the flue gas, a cleaning device can be utilized, regularly and automatically freeing the access tube of possible deposits with pressurized air impulses, as displayed in Figure 4.

Figure 4 - left: Cleaning device with pressurized tank. **right:** EUflame sensor with cleaning device mounted on boiler wall.

Each pyrometer gathers one dimensional temperature information by analyzing the integral of the gas radiation along the line of sight or measurement path. By acquiring one dimensional temperature information from multiple directions, a two-dimensional temperature map can be reconstructed with algorithms similar to those applied in computed tomography. [12]

Arbitrary temperature zones can be defined, in which the mean temperature value is calculated. These values can be then utilized for many different applications, e.g. tracking the temperature above individual burners or at the area of effect of individual SNCR injection lances.

With the patented burnout technology, an indication of combustion quality can be determined qualitatively and non-intrusive, as well. [12]

4 EREN Enerji Zonguldak ZETES II unit 3 - case study

4.1 System layout

The EUflame 2D system was put into operation for ZETES II unit 3 at the beginning of March 2023 at 45 m height, above the burners, but below the OFA. The sensor layout, as depicted in Figure 5 was chosen for optimal coverage of the furnace cross-section, while maintaining acceptable system outlay. One sensor was placed over each vertical burner row, while two more sensors on either side of the furnace were applied for the two-dimensional information.

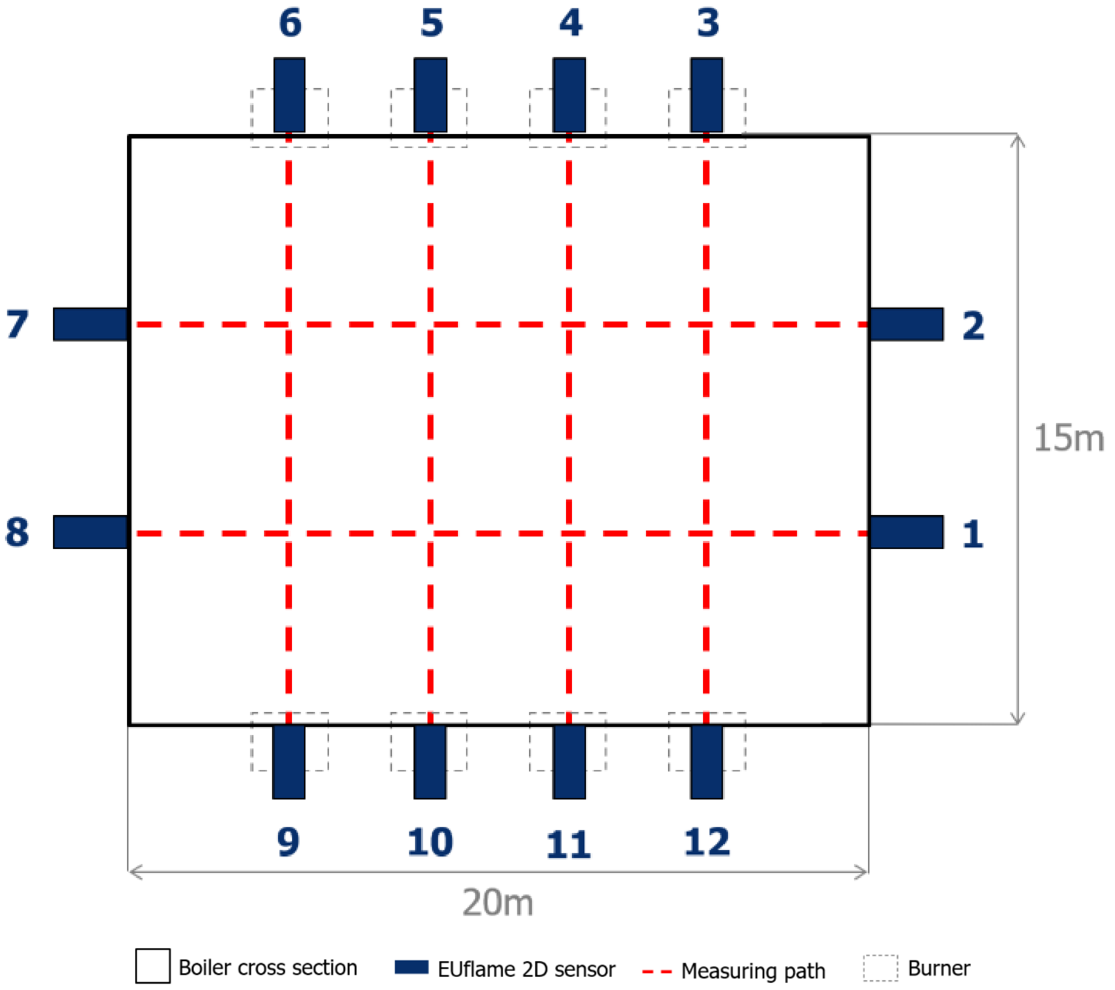

Figure 5: Initial EUflame 2D sensor layout at ZETES II unit 3.

4.2 Initial FEGT distribution and optimization

Directly after successful commissioning of the EUflame 2D system, the temperature distribution at the end of the furnace was shown to be inhomogeneous, as can be seen in the top graph of Figure 6. The temperature distribution had several suboptimal characteristics. A strong imbalance between front and rear of the boiler could be observed. Additionally, the flue gas on the left side of the boiler was hotter than on the right side, leading to a hot spot in the left upper corner. By calculating the standard deviation, the homogeneity of the temperature distribution can be quantified. The initial standard deviation of the FEGT distribution was about σ = 45 K. Following the explanation in Section 2.3, the low temperature in the lower right corner indicates a suboptimal air to fuel relation for at least one of the burners below this area.

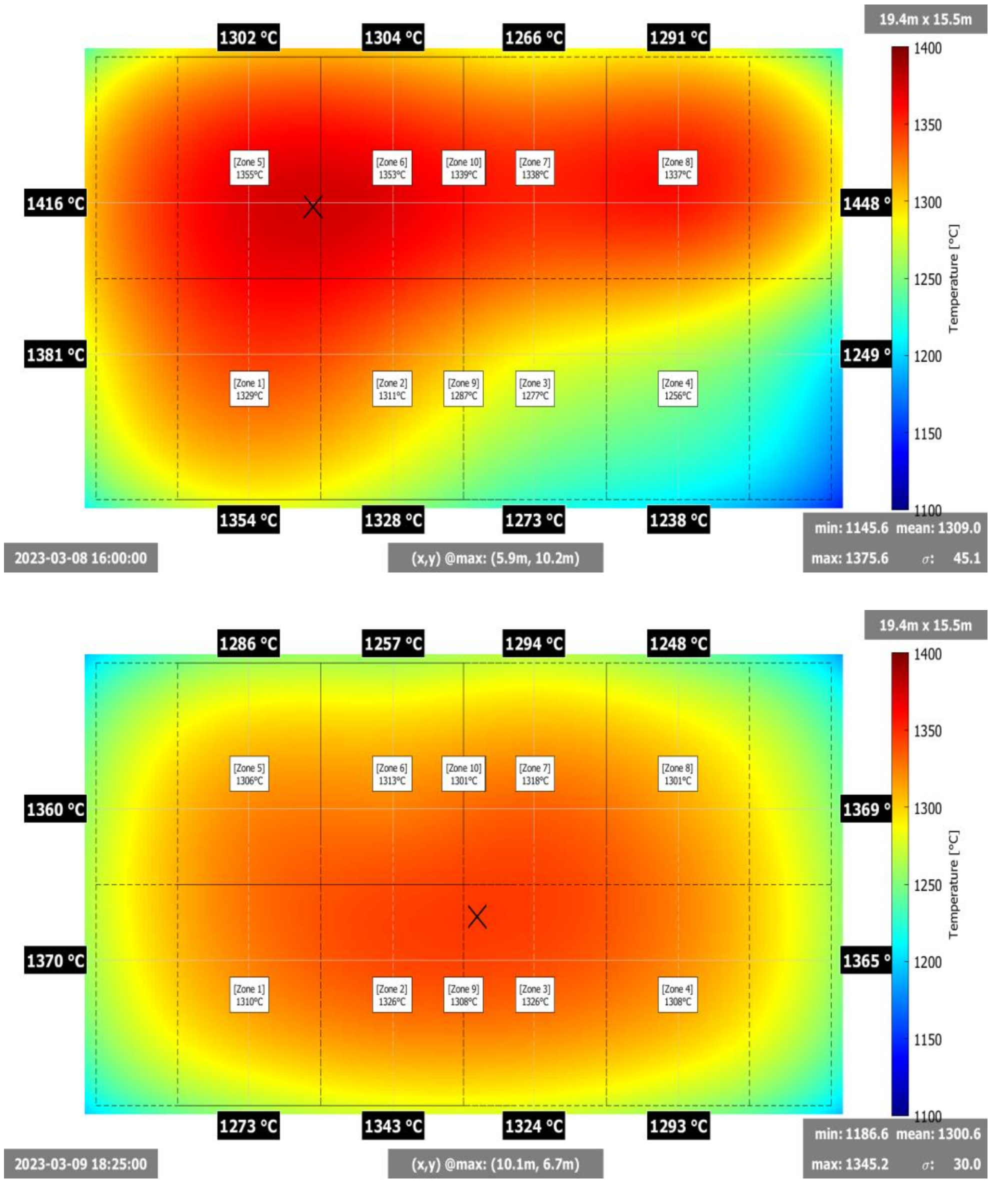

Figure 6: Gas temperature distribution over the cross-section at the end of the furnace measured and visualized by the EUflame 2D system. **top**: Initial state at commissioning; **bottom**: Optimized state one day after commissioning.

After this diagnosis, the distribution of air (e.g. secondary air and over-fired air) was adapted to homogenize the temperature distribution. Within one day of the commissioning of the EUflame 2D system, the temperature distribution depicted in the bottom graph of Figure 6 was achieved. Compared to before, several primary aspects of the FEGT have been improved. The FEGT distribution was substantially homogenized, with the previous temperature imbalance between left and right as well as front and rear greatly diminished. As a result, the spot of the highest temperature moved to the center of the boiler and away from the heat transfer surfaces, where it can facilitate high temperature corrosion. The maximum temperature was decreased. This is important in order to stay below the melting point of any slagging producing compounds [12]. At the same time, the minimum temperature was increased, leading to a reduction in temperature spread that can be quantified in a lower standard deviation of σ = 30 K.

4.3 Secondary effects

The initial optimization focused on the homogenization of the FEGT distribution via the adaption of the secondary air (SA) distribution. Achieving a homogenic FEGT distribution implies an improvement of combustion hygiene on the individual burner level, as described in Sections 2.2 & 2.3. In the case of ZETES II unit 3, this is reflected in a significantly decreased amount of excess O_2 in the flue gas, while at the same time CO and NO_x emissions were also lowered substantially, as can be seen in Figure 7 a).

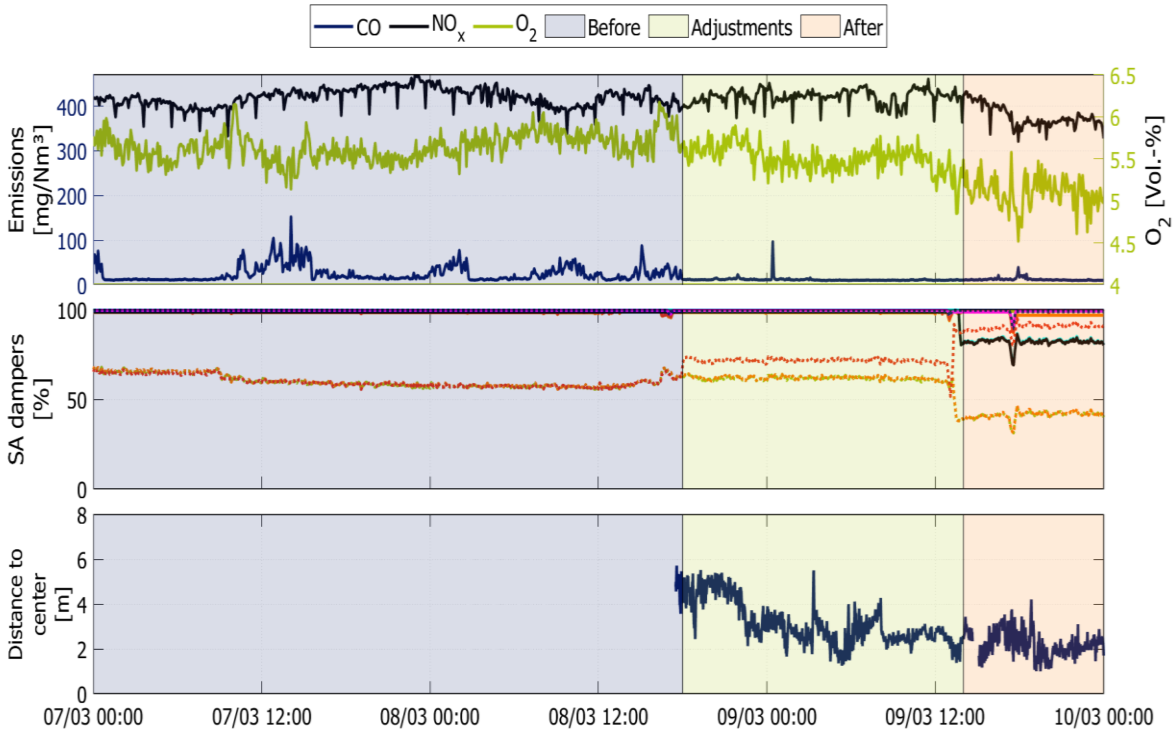

Figure 7: Various process quantities displayed over time and categorized as before, during, and after the optimization. **a)** Selected flue gas components. **b)** Secondary air damper positions. **c)** Distance of the hottest spot to the center of the furnace.

The average excess O_2 was lowered from 5.6 % to 5.1%, while at the same time CO was lowered from 25 mg/Nm^3 to 12 mg/Nm^3 and NO_x from 420 mg/Nm^3 to 375 mg/Nm^3. This was achieved in two sets of SA damper changes over the course of less than a day, as displayed Figure 7 b). In order two highlight the process of how the FEGT distribution was homogenized at the same time, the distance between the hottest spot and the center of the furnace is plotted in Figure 7 c). It decreases over the time of the optimization period from around 5 m down to 2 m. This is especially remarkable when considering the whole furnace dimensions of 15x20 m.

Figure 8 displays the important changes in the flue gas composition as histograms, where the effect of the optimization becomes even more pronounced. The spread of excess oxygen values stayed approximately the same, while the mean shifted from 5.6 % to 5.1% as mentioned above. The spread of the CO levels narrowed in at 12 mg/Nm^3, while values above 20 mg/Nm^{3}became outliers.

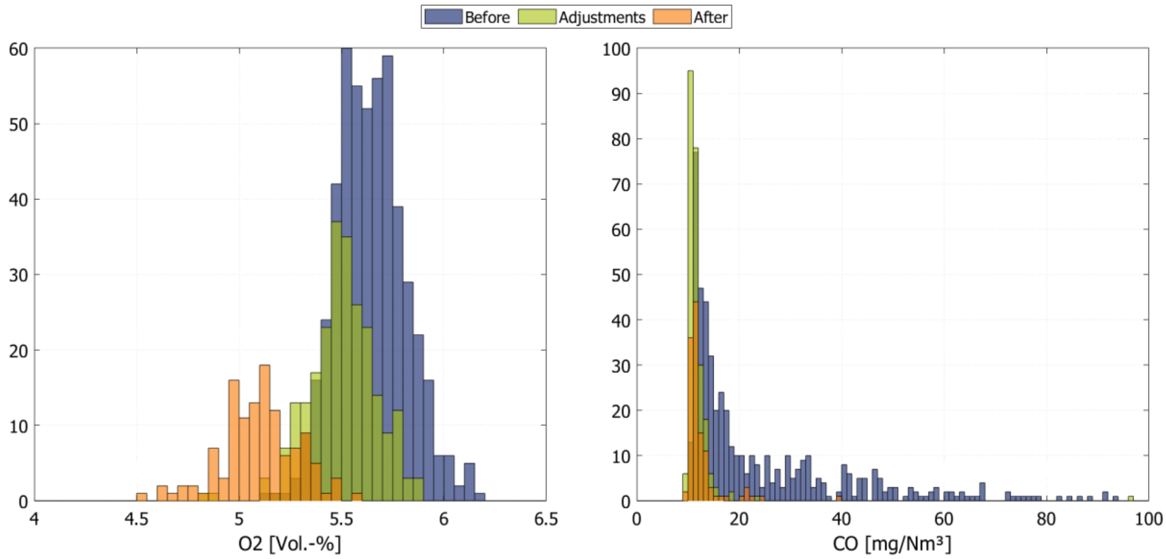

Figure 8: Histograms of excess oxygen (**left**) and carbon-monoxide (**right**), indicated as before, during, and after the optimization.

5 Summary and conclusion

Temperature is *the* diagnostic quantity in a combustion driven power plant. The temperature with the most general diagnostic value is the furnace exit gas temperature (FEGT). The EUflame 2D system by EUtech allows to measure and visualize the FEGT in absolute terms and its distribution with non-intrusive optical pyrometers. Within one day of the application of EUflame 2D, Eren Enerji was able to optimize the combustion process in ZETES II unit 3. This includes the homogenization of the FEGT and the resulting decrease of excess O_2, CO and NO_x at the same time.

6 Outlook

Since the commissioning of the EUflame 2D system, it is an integral part of the daily process control and diagnostic routine at ZETES II unit 3. In order to tackle more issues related to fouling and slagging, the EUflame 2D system has been upgraded from twelve (12) to sixteen (16) sensors to increase temperature resolution close to the heat transfer surfaces at the side walls. Furthermore, operators can account for the composition of the coal, by matching the highest temperature indicated by EUflame with the melting point of the coal compounds indicated by laboratory analysis. In this regard, the EUflame systems helps to reduce slagging substantially. In addition, it was understood from the FEGT that the combustion in the furnace was completed only high in the boiler, close to the superheaters. Subsequently performed CFD simulations showed that the problem was an inadequate burner design. After revision of the burners, the combustion level was moved lower in the furnace, the CO level decreased, and less combustion air was sufficient. The higher and more stable temperatures seen in the FEGT system after the revision, confirmed this situation. Additionally, the other boiler of ZETES II, unit 2, was equipped with a sixteen (16) sensor EUflame 2D system as well in order to reap the same benefits as with unit 3. Furthermore, Eren Enerji acquired an EUcoalflow mobile system by EUtech. This system allows for measurement of the pipe-to-pipe fuel distribution at each mill [13]. It can be utilized to detect pipe-to-pipe mass flow imbalances, track absolute mass flow to each burner, as well as the storage and release of fuel in the pipes due to changes in primary air. With the EUcoalflow system, Eren Enerji approaches the issue of proper AFR at each burner, as laid out in Sections 2.2 & 2.3, not only from the air side, but also from fuel side.

7 References

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