Online adjustment of Furnace Exit Gas Temperature field using advanced infrared pyrometry: Case study of a 1500 MW<sub>th</sub> utility boiler

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**ABSTRACT**

The Furnace Exit Gas Temperature (FEGT) is a key parameter of the combustion process in utility boilers that needs to be accurately monitored, especially in order to increase their load- and fuel-flexibility. However, neither the average FEGT nor its spatial distribution over the boiler cross section can be measured using standard equipment. Advanced pyrometry provides an accurate and efficient way to monitor the FEGT: by combining the signals from several pyrometers installed around the boiler, the FEGT 2D field can be reconstructed. In this paper, we show the results of a measurement campaign carried out on a 1500 MW<sub>th</sub> boiler using a system comprising 9 infrared pyrometers. Thanks to online adjustments of the combustion air distribution, the FEGT peak initially observed has been reduced by approximately 100°C, and the flame has been recentered.

1. Introduction

Due to the increasing importance of intermittent renewable sources in the energy landscape and the increasing trend towards the use of alternative fuels or fuel blends in heat and power production installations (such as lower-rank fuels or various solid, liquid and gaseous energy carriers), both load- and fuel-flexibility will soon become key technical features of thermal assets [1–3]. More frequent load variations and broader ranges of fuel characteristics both require a careful monitoring of key parameters of the combustion process compared to base load operation with a single, well-known fuel, especially in case of deviation from the original boiler design.

Together with air and fuel distributions [4,5], the Furnace Exit Gas Temperature (FEGT) is such a key parameter for utility boilers [6–9]. It is measured at the outlet of the furnace, upstream of the convective heat exchangers. It is a consequence of the amount of heat transferred to the evaporator in the furnace and it gives an image of the distribution between the radiative heat transfer to the evaporator and the convective heat transfer to the superheater(s), reheater(s) and economiser downstream of the furnace. In drum boilers, the heat transfer to the evaporator rules the produced steam flow rate and therefore, together with the residual sensible heat of

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Apart from its influence on the steam parameters, FEGT is also related to primary NO\textsubscript{x} production in the furnace as well as ash-related issues encountered with solid fuels. Due to their larger radiative heat transfer surface, large furnaces exhibit lower flame temperatures and lower FEGT's, hence lower thermal NO\textsubscript{x} productions and lower risks of slagging on the furnace walls. A lower FEGT also reduces the risk of slagging and fouling in the convective heat exchangers. FEGT is therefore often compared to the Ash Melting Temperature (AMT) of solid fuels. Although it is not sufficient to guarantee a low ash deposition rate, the FEGT should always be lower than the AMT. The delayed combustion promoted by low-NO\textsubscript{x} firing systems (at the level of the burners or the boiler) can however result in a higher FEGT.

The spatial distribution of FEGT across the boiler section also gives an indication of the position of the flames in the furnace and of the presence of local hot spots. Ideally, the temperature peak should be centered and not too high compared to the average. If not, it could cause an uneven distribution of the heat flux to the furnace walls and lead to tube failures. FEGT must also be carefully monitored when Selective Non Catalytic Reduction (SNCR) is used to reduce NO\textsubscript{x} [8]. The reagent must indeed be injected in the flue gas at the adequate temperature range (900-1100\degree C), which can be difficult to locate in case of load variations [10].

The accurate monitoring of FEGT is therefore crucial during base load operation in order to detect any deviation of heat transfer distribution (for instance due to ash deposition and/or unbalanced combustion), but it of course becomes of increasing importance when load- and fuel-flexibility are expected.

Despite its importance, FEGT is not properly monitored using the standard equipment available in utility boilers: a series of thermocouples generally measure local temperatures on both sides of the boiler at the exit of the furnace, close to the furnace walls. They only help following the trends of FEGT variations, generally during start-ups and shutdowns, but are unable to monitor the true average FEGT nor its spatial distribution across the boiler section. The average FEGT and its 2D distribution are sometimes assessed during commissioning, using grid measurements performed with long, water-cooled suction probes able to reach the center of the boiler. This time consuming process generally serves as a one-shot validation of the boiler design, or exceptionally for trouble-shooting purposes, but it cannot be used as a monitoring tool during normal boiler operation [9].

In the absence of any accurate measurement, the average FEGT can be estimated by carrying out heat and mass balances for the heat exchangers located in the furnace and in the flue gas path. Various techniques can be applied, including neural networks [7]. The accuracy of such assessment is however very much dependent on the chosen methodology and the accuracy of the available data. In addition, the validation of such results for various loads, various fuels and during transient phases is not straightforward. These methods are also unable to provide any assessment of the 2D FEGT field distribution.

Although it is not proposed as a standard monitoring tool yet by boiler manufacturers, advanced pyrometry is currently the most accurate technique for a direct measurement of the average FEGT and its distribution across the boiler section [8]. When combining several pyrometers spread over the boiler perimeter, the FEGT 2D field can be reconstructed [8], as will be shown in this study. Both acoustic and infrared pyrometric systems are available on the market. Acoustic pyrometers are based on the fact that the speed of sound depends on gas temperature. However, it also depends on the gas composition and the presence of soot or ash in the flue gas [6,8,9]. Refraction of the sound wave front by density and temperature gradients can also impact the measurements [8]. Recent studies focus on other issues related to the choice of the acoustic signal or the time delay estimation [9]. Infrared pyrometers are based on the
strong infrared emission of \( \text{CO}_2 \), that can be correlated to the gas temperature via the Stefan-Boltzmann law. They require less frequent cleaning than acoustic pyrometers \cite{8}. The use of advanced infrared pyrometry has already been validated at industrial scale, but little information can be found in the literature about the performances of such systems in large utility boilers.

In this paper, we present the results of the online monitoring and adjustment of the FEGT that was carried out on a 1500 MW\(_{th}\) utility boiler using advanced infrared pyrometry. The studied boiler presented an uncentered, high temperature peak at the outlet of the furnace. The boiler and the EUflame pyrometry system used in the frame of this study are described in Section 2. The results of the measurements carried out before and after the corrective measures that were taken are presented in Section 3.

2. Methodology

2.1. Boiler

The studied boiler is a subcritical, 45 m-high, two-pass boiler with a nominal thermal power of approximately 1500 MW\(_{th}\). Fig. 1 illustrates the general boiler arrangement. The combusted fuel is crude oil, but the methodology and the results of the present study about FEGT monitoring and adjustment are also valid for other types of liquid, gaseous or solid fuels. The width and the depth of the furnace are approximately 15 m and 12 m, respectively. Air staging is applied at both the level of the burners and the boiler. In the primary combustion zone, low-NO\(_x\) burners are operated under globally sub-stoichiometric conditions, with an air-fuel equivalence ratio in the range 0.8 – 0.92. The 24 burners are grouped in 6 rows (3 on the front side, 3 on the rear side). Over Fire Air (OFA) is injected in the combustion completion zone to secure the complete combustion of unreacted hydrocarbons and CO. OFA is injected through 12 air ports arranged in 2 opposed rows. According to the design documents, the nominal FEGT at full load is 1370\(^\circ\)C. In this study, the FEGT is measured approximately 4 m below the nose, and approximately 1 m below the cross section reduction. The nose is approximately 5 m deep. Both the primary and secondary superheaters (SH1 and SH2) are mainly convective (no radiant superheater), so that almost all the radiative heat transfer from the flame is absorbed by the evaporator in the furnace. At the time of this study, tube failures had been reported at the level of the OFA. A root cause analysis had shown that high local heat fluxes were probably one of the causes for these leakages.

2.2. Infrared pyrometers

The EUflame 2D system used in this study provides a complete temperature profile across the furnace cross-section by combining the signals from several infrared pyrometers installed around the boiler \cite{8}. Fig. 2 illustrates the mounting of an EUflame pyrometer on the boiler wall. 4 to 12 pyrometers are typically used. One of the main advantages of the EUflame system 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. Such systems can be used to monitor the FEGT in all types of utility boilers, but also the temperature distribution at the inlet of the Heat Recovery Steam Generator (HRSG) of combined cycle power plants, with or without duct burners.

In this study, a mobile system comprising 9 pyrometers was installed approximately 4 m below the nose of the boiler, and approximately 1 m below the cross section reduction, see Fig. 1. The detailed locations of the pyrometers around the boiler will be illustrated with the results of the carried out measurements, in Section 3. The measurements were carried out during stable operation of the boiler at full load, and the measured temperature fields were averaged over at least 15 min.

Fig. 2. An EUflame infrared pyrometer mounted on the boiler wall.
3. Results and discussions

3.1. Initial situation

The initial FEGT distribution exhibits a high, uncentered temperature peak, as illustrated in Fig. 3. The black dots indicate the location of the nine pyrometers. While the average FEGT is in line with the design value (1373°C), the maximum temperature is as high as 1556°C. Given the arrangement of the burners and the OFA ports around the boiler, the general pattern of the temperature field is...

Fig. 3. Initial FEGT distribution. Average: 1373°C; Maximum: 1556°C; Minimum: 1236°C; Standard deviation: 73°C. The black dots indicate the location of the nine pyrometers.

Fig. 4. Peak and average FEGT vs. relative OFA flow rate.

3. Results and discussions

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however as expected: a high temperature zone at mid-depth, spread over the width of the boiler. It should however be noticed that, although the peak temperature is reached at mid-depth, the average temperature is slightly higher on the front side (0 – 6 m depth) compared to the rear side (6 – 12 m depth). This is due to the influence of the nose, located approximately 4 m above the measurement plan, that directs the flow towards the front side, see Fig. 1.

3.2. Decrease of OFA flow rate

In order to lower the observed temperature peak, and therefore reduce the maximum local radiative heat flux in the upper part of the furnace, it was decided to reduce the OFA flow rate, while of course keeping the total combustion air flow rate constant. Fig. 4 shows the evolution of the peak and the average FEGT as a function of the relative OFA flow rate. The average FEGT remains constant for a reduced OFA flow rate, while the peak temperature is strongly impacted. When 65% of the initial OFA flow rate is reached, the observed peak temperature decreases by approximately 100°C (1457°C vs. 1556°C). The standard deviation over the temperature field decreases by 37% (46°C vs. 73°C). The observed FEGT distribution is illustrated in Fig. 5. The disappearance of the high temperature peak is obvious. The temperature field however remains slightly biased towards the right-hand side. The constant value of the average FEGT means that the total heat flux to the evaporator remains constant when more heat is released at the level of the burners. This is actually in line with the fact that the superheaters are mainly convective, and located above the nose: reducing the heat release in the combustion completion zone does not significantly affect the distribution of the radiative heat transfer between the evaporator and the superheaters. In boilers featuring radiative superheaters, the average FEGT and the superheated steam temperature could have been more affected. An impact was however observed on the desuperheater spray, probably due to the limited but unavoidable contribution of radiative heat transfer in the convective superheaters. Due to the non-linear dependence of radiative heat flux on the temperature, it globally increases in the presence of a hot spot. As expected, the desuperheater spray progressively closed when the peak temperature decreased.

Unfortunately, no accurate measurement of primary NOx emissions (at the outlet of the furnace) was available during these tests. Based on comparable tests performed on identical boilers, it can however be estimated that the reduced air staging between the primary combustion zone and the combustion completion zone resulted in an increase in NOx production of around 20%, which remained within the acceptable range in terms of final stack emissions.

3.3. Detailed adjustment of OFA distribution

In order to shift the flame to the centre of the boiler, further adjustments of the detailed distribution of OFA were performed. The OFA ports were open more widely on the left-hand side, leading to a global reincrease of the OFA flow rate (back to 73% of the initial
value), but also to a global rebalancing of the combustion air. The burner air and OFA distribution systems being connected, decreasing the global pressure drop on the left-hand side also resulted in increasing the burner air flow rate on this side. The discrepancy between the oxygen concentration measurements on both side of the boiler outlet was reduced from 0.78% to 0.47% (dry) after these additional adjustments. The resulting FEGT distribution is illustrated in 6. The average FEGT still corresponds to the design value (1370°C).

Despite the reincrease of the total OFA flow rate, the peak temperature is also still 100°C lower than the initial value (1453°C vs. 1556°C). The highest temperature region is however more homogeneously spread over the width of the boiler, which is line with the reduced discrepancy in O₂ concentrations.

Table 1 summarises the measured fuel and air flow rates corresponding to the operating conditions of Figs. 3, 5 and 6: initial situation, reduced OFA flow rate (−35%) and fine adjustments. The measured average and peak FEGT are also recalled.

### 4. Conclusions

In this paper, we showed the results of the online monitoring and adjustment of the FEGT distribution in 1500 MWₑ th utility boiler carried out thanks to an advanced infrared pyrometric system. 9 pyrometers were installed around the boiler and their signals were

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**Table 1**

|                     | Initial situation | OFA 65% | Fine adjustment |
|---------------------|-------------------|---------|-----------------|
|                     | Fig. 3            | Fig. 5  | Fig. 6          |
| Fuel flow rate [kg/s] | 33.9              | 34.2    | 33.4            |
| Burner air flow rate [kg/s] | 405              | 444    | 439             |
| OFA flow rate [kg/s] | 114              | 74     | 83              |
| Total air flow rate [kg/s] | 519              | 518    | 522             |
| Relative OFA flow rate [%] | 100%            | 65%    | 73%             |
| Average FEGT [°C]  | 1373              | 1362    | 1370            |
| Peak FEGT [°C]     | 1556              | 1457    | 1453            |
| Fuel LHV [MJ/kg]   | 42.2              | 42.2    | 42.2            |
| Air temperature [°C]| 311               | 311     | 311             |

**Fig. 6.** FEGT distribution after fine adjustment of the OFA openings. Average: 1370°C; Maximum: 1453°C; Minimum: 1278°C; Standard deviation: 43°C. The black dots indicate the location of the nine pyrometers.
combined to reconstruct the 2D FEGT field. The temperature peak initially observed was first reduced by approximately 100°C by modifying the combustion air distribution between the Over Fire Air (OFA) ports and the burners. The evolution of the peak FEGT as a function of the relative OFA flow rate was reported. Due to the specific design of the boiler, the average FEGT was not impacted. In a second step, the flame has also been centered thanks to a fine adjustment of the OFA port openings.

Due to the growing need for load- and fuel-flexible utility boilers, the use of advanced, online FEGT monitoring systems will soon become essential to ensure that both the average FEGT and its spatial distribution are adequate in all circumstances.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

J. Blondeau: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing - original draft. J. Van den Auweele: Conceptualization, Investigation, Methodology, Writing - review & editing. S. Alimuddin: Conceptualization, Investigation, Methodology, Writing - review & editing. F. Binder: Methodology, Software, Visualization, Writing - review & editing. F. Turoni: Conceptualization, Methodology, Supervision, Writing - review & editing.

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