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Combustion and heat transfer monitoring in large utility boilers

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Abstract — As a result of the quick and vast development of instrumentation and software capabilities, the optimization and control of complex energy systems can presently take advantage of highly sophisticated engineering techniques, such as CFD calculations and correlation algorithms based on artificial intelligence concepts. However, the most advanced numerical prediction still relies on strong simplifications of the exact transport equations. Likewise, the output of a neural network, or any other refined data-processing device, is actually based in a long record of observed past responses. Therefore, the implementation of modern diagnosis tools generally requires a great amount of experimental data, in order to achieve an adequate validation of the method. Consequently, a sort of paradox results, since the validation data cannot be less accurate or complete than the predictions sought. To remedy this situation, there are several alternatives. In opposition to laboratory work or well-instrumented pilot plants, the information obtained in the full scale installation offers the advantages of realism and low cost. This paper presents the case-study of a large, pulverized-coal fired utility boiler, discussing both the evaluation of customary measurements and the adoption of supplementary instruments. The generic outcome is that it is possible to significantly improve the knowledge on combustion and heat transfer performance within a reasonable cost. Based on the experience and results, a general methodology is outlined to cope with this kind of analysis. © 2001 Éditions scientifiques et médicales Elsevier SAS

boiler instrumentation / heat transfer / monitoring of heat transfer efficiency / fouling assessment

Nomenclature

A	heat transfer area	m^2
c_p	heat capacity	$J{\cdot}kg^{-1}{\cdot}K^{-1}$
F	correction coefficient	
h	enthalpy	$J{\cdot}kg^{-1}$
m	mass flow rate	$kg{\cdot}s^{-1}$
Q	heat transfer rate	W
R_f	thermal resistance due to ash fouling	$K{\cdot}m^2{\cdot}W^{-1}$
R_w	thermal resistance of tube walls	$K{\cdot}m^2{\cdot}W^{-1}$
T	temperature	K
t	time	s
U	overall heat transfer coefficient	$W{\cdot}K^{-1}{\cdot}m^{-2}$
w	relative flow rate	

Greek symbols

α	heat transfer coefficient	$W{\cdot}K^{-1}{\cdot}m^{-2}$
ε	uncertainty	

Subscripts

by-pass	by-pass to primary economizer
ext	external side
EZS	primary economizer — superheater pass
EZR	primary economizer — reheater pass
i	inlet section
int	internal side
lm	logarithmic mean
o	outlet section
PAP	primary air preheater
SAP	secondary air preheater
tot	total flow rate

1. INTRODUCTION

Even though performance monitoring (combustion, fluid flow, heat transfer, thermal efficiency) of large utility steam generators has experienced a strong development in recent years, it is still necessary to use complex models

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in order to characterize or to predict some phenomena not well understood. Two representative examples are the production of trace species in flue gases [1] and the fouling due to deposits on heat transfer surfaces [2, 3].

Advanced models comprise several techniques: Computational Fluid Dynamics, refined data correlation, and statistical methods combined with special measurements of fuel characteristics or boiler response. The results are expected to have a decisive influence within the current economic and technologic context, that demands from the plants a flexible operation, with variable and out-of-design load regimes and fuel qualities.

In most cases, an advanced mathematical model poses a curious problem: it generates a great amount of precise numerical values: velocity, concentration and temperature fields, irradiation profiles in the combustion chamber, heat transfer distribution in platens and tube bundles, evolution of emissions with time and load profiles, etc. For the purposes of validation, an adequate option could be the data measured under controlled conditions, i.e., those acquired at laboratory scale or in pilot or demonstration plants. However, this approach suffers from two basic shortcomings. Firstly, the physical processes involved in a power boiler are *per se* not physically scalable, and, as a consequence, small scale experiments can be only considered as approximations. On the other hand, an experimental installation of semi-industrial size involves very high investment and maintenance costs, so that it is only feasible at the design stage.

Many times, the only alternative to validate new analysis tools turns out to be the set of measurements acquired in the full-scale plant itself. This implies a fully different kind of limitations. The main one is that the data acquired under industrial conditions in large plants lack in many aspects the quality and completeness obviously provided by laboratory data. When we wish to decide if a given prediction is reasonable, not only the measurement uncertainty, but also the physical significance of many process signals can be questioned. On the other hand, a complete validation would often require such a large quantity of experimental determinations that it would be simply unfeasible. Finally, the data acquisition campaigns and any sort of additional measurement must always conform to production and safety requirements, without increasing significantly the maintenance costs of the plant.

Summing up, a careful validation requires an examination of the reliability of existing process data, and the design of new instruments and measurement procedures in order to supplement the information currently available and improve its quality. New experimental determinations are subjected to the limitations mentioned above. A practical equilibrium is very subtle, because it is not reasonable to attempt the theoretical levels that would require the actual process conditions, but neither to resign oneself to the customary and usually deficient practices.

In this report, a project aimed at the improvement of the instrumentation of an existing pulverized coal-fired utility boiler is presented. The unit is of fully-commercial size and features. The activities were related to the following topics: fuel and ash characteristics, water-steam data, air and gas temperatures, oxygen concentrations and relative flow rates through boiler convective sections, ducts, and air heaters. Evaluation of new monitoring capabilities offers a convincing result: the equilibrium above mentioned is favorable, and a minimum investment can produce very significant improvements. In view of the diverse technical difficulties encountered, and the solutions adopted, a possible general methodology is presented, that far from being only valid for this particular case-study, can be applicable to a general situation.

2. METHODOLOGY OF ANALYSIS

Figure 1 presents a sketch of the proposed methodology. The first part involves a complete and detailed inventory of all available data and their evaluation according to significance, reliability and uncertainty. As a general rule, available process information can be classified as follows:

- conventional continuous process data,
- plant measurements taken with portable instruments,
- information obtained from sample analysis (coal and ash),
- special measurements.

Determination of the physical significance requires to know the location of instrumentation in the plant, its technical specifications, control schemes, assembly and flux

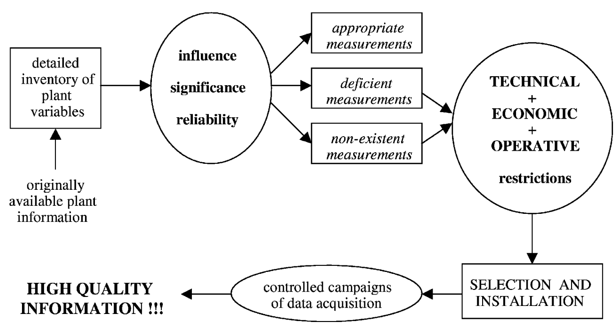

Figure 1. Schematic diagram of the proposed methodology.

diagrams. The thermal analyst has to relate this information with the calculations he or she intends to perform. As an example, the overall fouling resistance of convective sections can be evaluated from the measurement or estimation of gas and steam temperatures and flows. In principle, this poses no major inconvenience, but in this unit, the flue gas stream is split in two separate boiler passes, as a means to control reheated steam temperature. The problem is then to estimate the share of combustion gas flowing through each boiler bank, an almost impossible physical determination, due to the large size, the intricate geometry, the high temperatures, and the erosion potential of the ash-laden medium. As a rule-of-thumb, boiler operators think in terms of fixed proportions, given by the position of the dampers that effect the control. Although this is obviously meaningful, it is by no means quantitative, since the flow rates would not be proportional to the damper positions, and moreover, the effective pressure loss coefficient of the dampers is unknown.

Uncertainties are determined according to the above classification. In the case of conventional plant data, the following sources or error are typically considered:

- installation effects,
- signal transmission errors,
- signal compensation errors,
- errors due to calibrations carried out during plant operation.

Compared with these effects, the uncertainty of the measurement principle is usually negligible. The case of air flow metering may serve as a good illustration of this kind of analyses. In power station boilers, conventional differential pressure flow meters are used to estimate the different air streams entering the unit. However, the large size prevents them from meeting the standard geometries and the up- and downstream requirements of distance to singularities. For the same reasons, the instruments cannot be calibrated by conventional methods, neither *in situ* nor at a calibration shop. The discharge coefficient offered by the boiler supplier is then a nominal figure, calculated by standard methods [4] for an ideal instrument that conforms all the requirements. Surprisingly, it is also customary to ignore the compensation of gas temperature. As a consequence, the indication of air flows in the control room is intrinsically inaccurate, and cannot be used for a rigorous analysis of thermal performance of the steam generator.

For measurements obtained by means of portable devices, the error derived from the manual operation of the instrument must be also taken into account. For example, measurements of CO, O_2 or NO_x concentrations in combustion gases is conditioned by a previous calibration of the analyzer cell and a field verification of the gas-sampling procedures. Otherwise, mistaken values are obtained. Finally, the information from laboratory analysis of samples of coal and ash is mainly subjected to errors due to a lack or representativity of the sample, given the large size of hoppers and the temporal variability of the fuel supply. Standard procedures exist for assuring this representativity [5], but logically are very demanding and often not followed.

After the existing plant information has been evaluated, the second part of the methodology consists in drawing a preliminary list of all modifications and additional measurements needed to improve the monitoring. Obviously, the list will depend on the particular objectives pursued. For instance, a variable such as a relative gas flow is of interest for detailed thermal balances, but not for an overall, separate-losses calculation, since the latter only considers total input/output flows. The list should establish a preference order as a function of measurement significance, and it will have to be submitted for a feasibility study, including technical and economic restrictions. An additional recommendation that can be very useful is the dependence between variables. For example, if some flow rates can be determined by means of mass and energy balances (pressures and temperatures known) with an acceptable accuracy, the installation of new flow meters can be ruled out.

Aside from all these restrictions, plant operation planning should be also taken into account. If a long shutdown is needed to install or modify instruments, selected solutions can be unfeasible. Only at this point it is possible to undertake a detailed technical specification of selected new instruments, as well as the required modifications of the existing ones. As the final stage of the process, it is desirable to carry out a complete set of plant tests under controlled conditions. The main reason is that some instruments can only be installed temporarily with the aim of correcting conventional instrumentation indications. Operating conditions to be maintained during the tests should be in accordance with the production schedule, and will be conditioned to the real interest of the plant management staff in understanding and optimizing their production processes.

3. CASE-STUDY: TERUEL POWER STATION

The methodology of analysis described above, aimed at the application of advanced engineering models to large utility boilers, has been exercised in unit 2 of Teruel power station since 1997. This power plant, owned by Endesa (Spain), is composed of 3 units of 350 MW_e nominal gross load each, burning blends of domestic and imported coals. The boiler generates 1 100 $t \cdot h^{-1}$ of main live steam, at 540 °C and 170 bar. It is a front wall-fired unit, of natural circulation design, with three stages of superheat, single reheat, two economizers, balanced draft, and primary and secondary air preheating.

3.1. Review of existing instrumentation

Available process data in Teruel power station illustrate the standard practices in this kind of installations. The quality of many measurements is more than adequate for operational and control purposes, but not for the accurate calculations effected by advanced models. *Table I* summarizes the main deficiencies detected during the evaluation of existing plant measurements and the proposed solutions. These observations can be divided in three groups: determination of air and gas flow rates, temperature and concentration measurements in air and gas ducts, and coal and ash data.

The layout of air and gas ducts in power boilers is very compact and features large cross-sectional areas and the presence of many singularities: control and shut-off dampers, probes, bends, tees, etc. The flow is therefore expected to possess multiple velocity components and non-uniform and non-developed profiles. Consequently,

TABLE I
Deficiencies of customary power boiler instruments, and solutions proposed.

Variables	Existing deficiencies	Solution
Air–gas preheating circuit		
Air flow rates (primary, secondary and tempering)	Flow meters design and installation are not in accordance with standards. Calibration is unfeasible.	Discharge coefficient correction through plant tests by means of transverse methods using Pitot tubes with thermocouple probes, following EPA and ISO recommendations.
Air and gas temperatures in large ducts	Single measurement point. Subjected to thermal stratification error, estimated higher than ±10 %	Installation of thermocouples grids in selected sections of each duct.
Flue gas O_2 concentration in large ducts (on-line measurements)	Only two probes at boiler outlet section and a single probe at the impulsion section of the induced draft fans. Some deficiencies in calibration. Total error of ±13 %	Multipoint grid measurements by means of portable analyzers. Assessment of typical distributions from plant test results. Correlation with on-line measurements.
Relative gas flows in air preheating ducts	Determination by means of thermal balance to air preheaters. Estimated uncertainties of 8 % (primary) and 14 % (secondary).	Installation of flow meters is unfeasible. Previously presented solutions in this list help to reduce total uncertainty.
Boiler		
Gas temperatures inside the boiler (furnace and heat recovery sections)	Portable infrared pyrometer is used. Measurement of unknown precise significance in a participating medium with spectrally-dependent properties.	Installation of on-line meters is expensive and only provides qualitative information. The use of suction pyrometers is recommended in the case of high temperature sections.
Feed water flow rate	Wrong physical location of throat tap nozzle measuring this flow rate, not meeting the standards.	No proposal was issued. Installation of upstream straightener vanes is possible and would render acceptable accuracy.
Main and reheated steam flow rates	Obtained directly by means of turbine first stage pressure method. There is no reference to check them.	Flow coefficient recalculation from cycle isolated tests. Closure of mass and thermal balances for all existing flows.
Coal and ash information		
Laboratory analysis of coal and ash	Errors frequently greater than 10 % due to non-homogeneity of samples during normal plant operating conditions.	Adaptation of sampling procedures to standards requirements. Design of guidelines to improve coal homogeneity during plant tests.
Coal fineness	Sample procedure does not comply with any standard, and probably is highly sub-kinetic.	Use of isokinetic sampling probes in pulverized coal ducts.

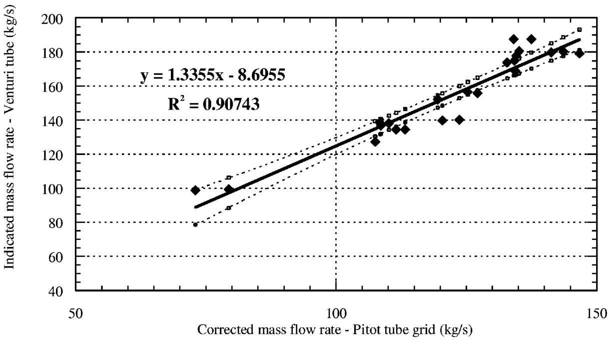

Figure 2. Correction of a secondary air flow meter. Broken lines represent 95 % confidence limits for individual observations.

as mentioned above, the use of conventional, pressure difference air flow meters is far from accomplishing the standard requirements [4]. Although the total air entering the boiler can be estimated by alternative means (combustion balance, characteristic curves of the fans), it is essential to know the relative air flow rates for undertaking any performance analysis of air preheating, milling or combustion equipment. There are six different air streams: primary (pneumatic transport of fuel), secondary (combustion), and tempering (temperature control), with two parallel lines for each. In order to correct the indication of the flow meters, a recalculation of their discharge coefficients was carried out during plant tests. For this purpose, multipoint grids of velocity measurement by means of Pitot static tubes were inserted in the corresponding duct.

As an example of the results, *figure 2* shows the relationship between the indication of a secondary Venturi and the mass flow rate calculated from Pitot tubes. Despite the presence of some outliers, the regression is quite satisfactory, confirming the hypothesis of a large systematic error. The combined figure for all six instruments is surprisingly high: +23 %. This result is coherent with previous works accomplished in the same power plant [6], that predicted a total deviation of 20 % from the comparison between combustion balances and forced draft fans' calculations.

This example can illustrate very effectively the equilibrium between theoretical requirements and practical shortcomings. If, as a guide, standard recommendations [7, 8] were to be strictly satisfied for the design of Pitot tube arrays, the number of velocity measurements per duct section would be very high. For instance, in the secondary duct of rectangular cross section, the recommended minimum is 32. Not only the material and maintenance, but also the personnel requirement would be excessive, because a short time of measurement is advisable to assure stable conditions. Consequently, it was decided to adopt a less-intensive grid, made up of 16 sampling points (4 instruments at 4 insertion depths).

Concerning the measurement of temperature and species concentration in air and gas ducts, similar observations apply. Typically, single or double probes are used in compact ducts of large cross-sectional area. This indication possesses a high uncertainty due to strong stratification of the flow pattern [9]. Furthermore, cases have been observed in which the probe was located in a reversed-flow or stagnation zone, leading to a completely unrealistic measurement.

The remedy is to use a grid of multiple measuring points in the duct section. Again, an equilibrium should be attained between the most cautious demands dictated by the specialized literature and standards, and the practical possibilities of realizing them. In our case, we used detailed profiles determined during early acceptance tests to infer a typical error probably higher than $\pm 10\,\%$ in the customary indications of temperature. Analysis of the temperature profiles lead to an optimum grid of 12 measurements points (4 instruments $\times$ 3 depths) in the 25 m^2 largest sections. Recommendations from accepted standards [10] are far more restrictive (1 point$\cdot m^{-2}$ of equal area), but are not warranted from a practical standpoint.

Other important conclusions are those related with coal and ash characteristics. Obviously, laboratory methods used in proximate and ultimate analysis and HHV and fineness determinations are highly accurate and very reliable. The problem rather lies in the sampling procedures. Focusing on the most important data, which are those pertaining to coal, neither sampling of raw fuel in the main belt, nor sampling of pulverized coal in burners' ducts are in accordance with standards. In the first case, discrepancies are related with the transport system and the capacity of sampling devices, and in the second case, with the use of non-isokinetic procedures. This can lead to a sample being non-representative of the actual fuel entering the unit. The only solution is to adapt the routine sampling systems and procedures to standard practices, and try to assure a homogenized coal feedstock during the development of specific plant tests.

3.2. Installation of new instruments

At the same time as corrections of existing measurements were considered, a study of absences in boiler instrumentation was also undertaken. These absences should be analyzed from the point of view of validation

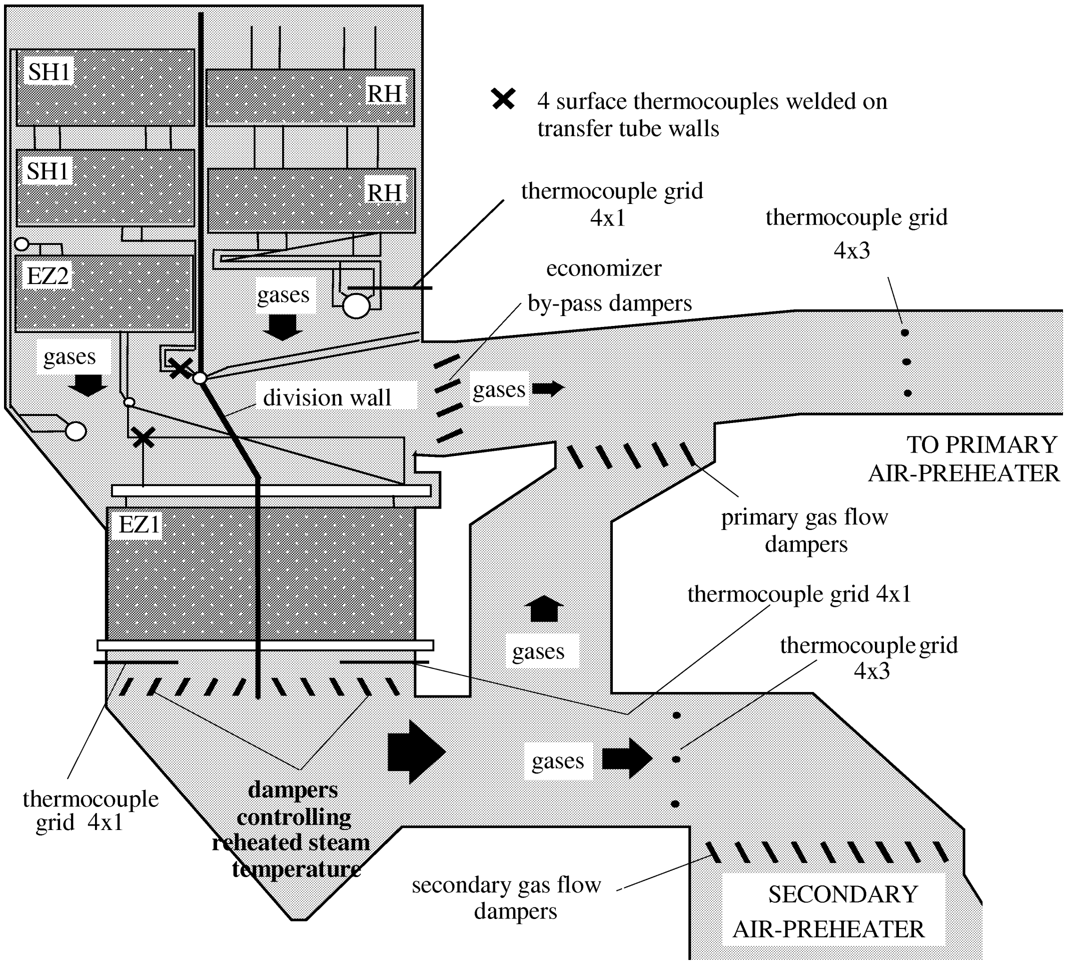

Figure 3. Thermocouple grids at boiler exit.

requirements. In the case of Teruel power station, key variables for detailed boiler thermal balances were unknown, and the activities were directed towards this problem.

Regarding relative gas flow rates through the boiler parallel passes, the only indication originally available is the position of the control dampers, *figure 3*. As already mentioned, the pressure loss coefficient is unknown, so that a reasonable estimate of the gas flow division is impossible. A theoretical or semi-empirical calculation can be undertaken in any case, but the large dimensions of the dampers, the irregularity of the velocity profiles and the thermal inertia of the process, which essentially implies unsteady state heat transfer, would probably render inconclusive this possibility.

On the other hand, direct flow rate measurement is complex and expensive in such a harsh environment, so that the only viable technical solution turned out to be much more simplistic. A control volume, approximately adiabatic, can be imagined at the boiler exit, having as entry sections the outlet of the two inner boiler passes and the gas by-pass, and as outlet sections the four (2×2 parallel lines) entrances to the air preheaters, *figure 3*. The idea is to measure an adequate average temperature on all these surfaces, and close the mass and energy balances of the control volume. This allows the calculation of relative gas flow through each boiler pass and air preheater. The flows so determined directly represent the average one must consider when calculating boiler tube banks as separate heat exchangers. The detail of the balance equations is as follows:

$$m_{\text{tot}} = m_{\text{SAP}} + m_{\text{PAP}} \tag{1}$$

$$m_{\text{by-pass}} h(T_{\text{o,RH}}) + (m_{\text{PAP}} - m_{\text{by-pass}}) h(T_{\text{i,SAP}}) = m_{\text{PAP}} h(T_{\text{i,PAP}}) \tag{2}$$

$$m_{\text{EZR}} + m_{\text{EZS}} = m_{\text{SAP}} + m_{\text{PAP}} - m_{\text{by-pass}} \tag{3}$$

$$m_{\text{EZR}} h(T_{\text{o,EZR}}) + m_{\text{EZS}} h(T_{\text{o,EZS}}) = (m_{\text{EZR}} + m_{\text{EZS}}) h(T_{\text{i,SAP}}) \tag{4}$$

where $T_{\text{o,RH}}$, $T_{\text{o,EZS}}$, $T_{\text{o,EZR}}$, $T_{\text{i,PAP}}$ and $T_{\text{i,SAP}}$ are measured temperatures, the total gas flow rate m_{tot} is obtained by means of combustion calculations and the primary gas flow rate m_{PAP} is estimated through a thermal balance of the air preheater. Considering that gas enthalpies can be calculated as $h(T) \approx c_p T$, and that all the temperatures above are of the same order of magnitude, so that c_p is roughly a constant, equation (4) leads to

$$w_{\text{EZR}} = \frac{m_{\text{EZR}}}{m_{\text{EZS}} + m_{\text{EZR}}} = \frac{T_{\text{i,SAP}} - T_{\text{o,EZS}}}{T_{\text{o,EZR}} - T_{\text{o,EZS}}} \tag{5}$$

for the relative gas flow rate w_{EZR} through the reheater pass of primary economizer.

Figure 3 shows the number and position of all the additional thermowells involved in these measurements. Although more probes would surely allow more accurate calculations, present results are deemed very coherent and satisfactory. The method has, however, an intrinsic shortcoming. The uncertainty of the calculated relative flow is, from equation (5):

$$\varepsilon(w_{\text{EZR}}) = \left\{ \frac{\varepsilon^2(T_{\text{i,SAP}})}{(T_{\text{o,EZR}} - T_{\text{o,EZS}})^2} + \left(\frac{(T_{\text{i,SAP}} - T_{\text{o,EZS}})\varepsilon(T_{\text{o,EZR}})}{(T_{\text{o,EZR}} - T_{\text{o,EZS}})^2} \right)^2 + \frac{\varepsilon^2(T_{\text{o,EZS}})}{(T_{\text{o,EZR}} - T_{\text{o,EZS}})^2} \right\}^{1/2} \tag{6}$$

Hence, the method produces an infinite error when the temperatures at the exit of two boiler passes, $T_{\text{o,EZR}}$ and $T_{\text{o,EZS}}$, are exactly equal, independently of the uncertainties $\varepsilon(T)$ in the temperature measurements. However, this is seldom the case, and it is estimated that a difference of only 3.5 °C causes less than 2 % of error in gas flows. Similar procedures may be applied in other cases of in-boiler flue gas distribution.

Considering the water-steam circuitry, there were not temperature and pressure probes at several headers connecting boiler sections. In the case of external transverse headers, temperature measurements were supplemented per boiler sides, installing 2 steam thermocouples at primary and final superheaters outlet sections and 2 steam thermocouples at reheater outlet section.

More difficult technical problems appeared when attempting to instrument water and steam headers located inside the boiler enclosure. The standard design does not include any instrument here, yet they are necessary to close the thermal balances in a per-boiler-section basis. Thermowells equipped with an armored outfit can be applied in this situation [11], welded in the header itself, or most conveniently, in intermediate transfer pipes. However, several doubt arose as to the integrity of the probes (and thus of the pressure circuit itself), as well as to the life-span of the metallic sheaths protecting electric cables.

As a compromise, surface thermocouples were mounted on transfer pipes, drawing the sheaths along the rear stagnation zone, where they are less exposed to the ash-laden gas flow. *Figure 3* shows their number and location. Although the measurement failed to indicate correct water or steam temperature, which was expected due to the small but not negligible thermal resistance of the weld and tube wall, it could be used to track relative variations. Furthermore, after more than 4 000 hours of operation, the sheaths were inspected and found in a good state of conservation, thus confirming the possibility of this kind of measurement.

4. CONCLUSIONS

As an example of the end results obtained by this cluster of systematic instrumentation improvements, *figure 4* shows the variation of thermal resistances R_{f} due to ash

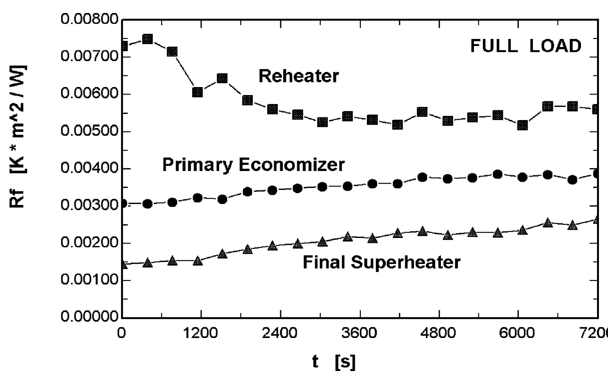

Figure 4. Calculated fouling thermal resistances during continuous plant operation.

fouling in reheater, primary economizer and final superheater, as calculated during normal plant operation via the new measurements installed. In order to calculate this rather relevant operational datum, we applied the standard lumped model of a heat exchanger:

$$Q = UAF\Delta T_{\mathrm{lm}} \tag{7}$$

$$UA = \frac{1}{1/(\alpha_{\mathrm{ext}}A_{\mathrm{ext}}) + R_{\mathrm{f}} + R_{\mathrm{wall}} + 1/(\alpha_{\mathrm{int}}A_{\mathrm{int}})} \tag{8}$$

where adequate estimations should be made of the gas and steam heat transfer coefficients α_{ext} and α_{int}, taking into account convective and radiative heat transfer. In the case of high temperature superheaters, equations (7) and (8) were also corrected for directed radiation fluxes, following the methods outlined in [12].

The values of thermal resistances are fully coherent with literature figures for coal combustion, and moreover exhibit correct trends which reflect progressive fouling, cleaning during load changes, and cleaning under steam blowing. The example presented in *figure 4* corresponds to 2 hours of continuous stable boiler operating period, at full load, with a moderate fouled situation. Operators of Teruel power station now use this kind of information to guide some of their maneuvers.

In general, it is concluded that normally available information in large plants often lacks the quality and completeness required by advanced monitoring and predictive engineering tools. However, plant measurements can be preferable to other alternatives, due to their simplicity and realism. This paper has reported some activities aimed at improving these aspects, as applied to a commercially operated utility boiler of large size. A more or less generic methodology has been also presented, which sums up to classify signals as a function of their quality and accuracy, correct observed deficiencies and meet important absences.

As the final conclusion, it is possible to substantially improve the knowledge on the performance of complex processes with relatively simple actions, thus maintaining a very conservative demand for additional resources, both in engineering and material investment and in personnel and maintenance expenses.

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