BEHAVIOR OF A HIGH-CAPACITY STEAM BOILER USING HEAVY FUEL OIL. PART II: COLD-END CORROSION

Félix Barreras[1,§], Jorge Barroso[2,*]

[1] LITEC/CSIC, Maria de Luna 10, 50018 Zaragoza, SPAIN
Ph.: +34 976 716 303, Fax: +34 976 716 456, e-mail: felix@litec.csic.es

[2] CECYEN, Universidad de Matanzas, Autopista a Varadero, km 3½, 44740 Matanzas, CUBA
Ph.: +53 45 261 432, Fax: +53 45 253 101, e-mail: barroso@litec.csic.es

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[§] Corresponding author
[*] Present address LITEC/CSIC, María de Luna 10, 50018 - Zaragoza, SPAIN

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Ph.: (+34) 976 716 303, Fax: (+34) 976 716 456, e-mail: felix@litec.csic.es

[2] CECYEN, Universidad de Matanzas, Autopista a Varadero, km 3½, 44740 Matanzas, CUBA

SUMMARY

An experimental study has been performed on a high-capacity steam boiler burning heavy fuel oil to assess cold-end corrosion damages. In this second part of the research, acid corrosion in the rotary continuous-regenerative air heaters (CRAHs) has been analyzed. Corrosion potentiality has been evaluated from both qualitative and quantitative viewpoints. Results have shown that acid corrosion in the CRAHs is reduced when the low-quality heavy fuel oil is mixed with a magnesium-based additive. In this research, two commercial additives have been tested: a magnesium oxide-based slurry and an organometallic one. The best results have been obtained when the organometallic additive was used in the treatment of the heavy fuel. For this experimental condition, an increase in the useful lifetime of the pie-shaped baskets, as well as a decrease in both the acid dewpoint temperature at the stack gases and the pressure drop (fouling) on the CRAHs have been confirmed.

Keywords: *Acid corrosion, Vanadium, Magnesium, Additive, Steam boilers*
Short title: *Low-temperature corrosion in steam boilers*

[§] Corresponding author
[*] Present address LITEC/CSIC, María de Luna 10, 50018 - Zaragoza, SPAIN

NOMENCLATURE

A	area of the coupons [mm^2]
ADT	acid dewpoint temperature [$°C$]
a	width of the coupons [*mm*]
B	total fuel oil consumption [*t/year*]
CR	corrosion rate [*mm/year*]
$CRAH$	rotary continuous-regenerative air heater
ΔP	weight loss [*g*]
e	thickness of the coupons [*mm*]
G_{Add}	additive consumption [*l/year*]
G_{dw}	unitary volumetric flow of distilled water used in cleaning process [*$/cleaning*]
G_{cs}	unitary volumetric flow of caustic soda used in cleaning process [*$/cleaning*]
l	length of the coupons [*mm*]
n_c	number of cleaning
P_{Add}	unitary price of additive [*$/l*]
P_{ass}	assembly/replacement price of one pie-shaped basket [*$*]
P_{dw}	unitary price of distilled water [$\$/m^3$]
P_{cs}	unitary price of caustic soda [*$/kg*]
P_{fo}	unitary price of fuel oil [*$/t*]
P_m	manufacture price of one pie-shaped basket [*$*]
q_1	cost of fuel oil overconsumption due to cleaning process [*$/year*]
q_2	cost of fuel oil overconsumption due to maintenance process [*$/year*]
R	magnesium-to-vanadium ratio
RBU	rate of acid build-up [$\mu A/min$]
R_{fa}	fuel oil-to-additive ratio [*t/l*]
r	radius of the fixing hole on the coupons [*mm*]
SI	International Unit System
ρ_m	density of the steel [kg/m^3]
t	exposure time of the coupons to the flue gas atmosphere [*h*]
UL	useful lifetime of the pie-shaped baskets [*year*]
Z	total cost for fuel oil and additive used to steam generation [*$/year*]

1- INTRODUCTION

Combustion of heavy fuel oil with high vanadium, sulfur and sodium contents, results in highly corrosive deposits in both high and low-temperature areas of the boiler. High-temperature corrosion is mainly caused by growth of ash deposits formed by compounds with low melting point, as V_2O_5. Cold-end corrosion, on the other hand, depends on the formation of sulfuric acid in the exhaust gases that can condense over the metal surface. During the combustion of sulfur-bearing fuel, the sulfur is readily oxidized to SO_2 during the combustion reaction prompted by the high temperature, and subsequently SO_3 is formed in the flue gases. The free SO_3 can react with water vapor in the combustion gases, forming sulfuric acid, H_2SO_4, and causing severe cold-end corrosion. Condensation of H_2SO_4 can occur directly on the metal walls of the heat exchangers in the low-temperature area and stack linings giving rise to cold-end corrosion, but also on soot particles, which will adhere to the surfaces resulting in a build-up of soot deposits, as well as potential acid smut emissions.

Cold-end corrosion potentiality is closely related to acid dewpoint temperature that is, in turn, function of the water vapor and acid species concentration in the flue gas. For this reason, the exhaust gases temperature is normally selected in boilers in such a way that the metal surface temperature in the last heat recovery elements is fixed several degrees above the acid dewpoint temperature to avoid its condensation. However, from a technical viewpoint, the major heat loss in boilers corresponds to that carried out with the exhaust gases. Hence, to increase the efficiency of the steam power unit, a reduction in the flue gases temperature exiting the boiler has to be achieved.

Probably the best choice to prevent cold-end corrosion is the change to a “lighter” fuel oil. This option allows for a more efficient combustion with a lower excess air, reducing both the amount of water vapor formed, and the SO_3 concentration on the combusting gases, leading to a lower sulfuric acid concentration in the flue gases. However, considering the present continuous reduction in the quality of liquid petroleum, this possibility usually ends up being just a wish, and alternative solutions have to be taken into account. Design aspects of the low-temperature heat exchangers, such as selection of appropriate materials, suitable flow velocity, etc., are to be considered. The use of porcelain-based coating products is becoming popular today, but in some particular situations the industrial investment cannot afford that either. When heavy residual liquid fuel oil is combusted, the use of chemical products like combustion catalysts and additives can be effective in controlling acid corrosion. Combustion catalysts can reduce the formation of sulfuric acid while magnesium-based additives neutralize the acid after it is formed. It is well known that alkaline metals (sodium and potassium) are suitable to neutralize SO_3 formation during combustion [1-4].

In this work, as in the previous one performed on the high-temperature corrosion area [5], two commercial additives have been tested: a magnesium oxide-based slurry and a liquid organometallic one. The benefits of these additives are demonstrated considering both the cold-end corrosion damages and the techno-economical viewpoint when the high-capacity boiler uses heavy fuel oil.

2.- EXPERIMENTAL

2.1- Experimental facilities

The present research has been developed in a high-capacity steam boiler of an electric power plant with a maximum power of 340 *MW/h* that is thoroughly described by Barroso et.al in Ref. [5]. In summary, the high-capacity steam boiler (see Fig. 1 in Ref. [5]) has 16 steam-assisted burners distributed in four floors, placed tangentially in the corners of the furnace to induce a vertical swirl motion of the combusting gases. The boiler burns 70 *t/h* of fuel oil to produce a maximum of 1,010 *t/h* of superheated steam with a pressure of 18 *MPa* and a temperature of 540°*C*. A 4-stage superheater, a 3-stage reheater, one economizer and two rotary continuous-regenerative air heaters form the heat recovery scheme. These last pieces of equipment are the target of the cold-end corrosion study performed in this work. They are vertical *Ljungstrom-type*; with a slow-turning rotor that is packed with closely spaced heat transfer elements. The rotor turns into the gas streams, picking up heat from the flue gas and transferring it to the combustion air.

This experimental research covers the same 4-year period described in Ref. [5]. In the first year, a regular (low vanadium content) fuel oil was burned, while from the 2nd to the 4th year, a heavy residual oil with a high vanadium content was used as fuel. The average physicochemical properties for these two fuel oils are summarized in Table 2 of Ref. [5]. Unexpectedly, in the beginning of the research, when regular fuel oil was still burned, visual inspection during the regular scheduled maintenance shutdowns of the boiler revealed that most of the pie-shaped “baskets” of the rotary continuous-regenerative air heaters were dramatically corroded. When the heavy residual fuel started being used, the large amount of vanadium, sulfur and sodium caused a worse combustion, an increase of fouling on the heat exchange equipments, and serious corrosion damages in high- and low-temperature areas of the boiler.

In the present research, to reduce or prevent cold-end corrosion, the effects of two commercial additives mixed with the heavy residual oil have been studied, a magnesium oxide-based slurry and a liquid organometallic one, which are two of the most popular additives used in boilers [6]. The magnesium oxide-based slurry is a grayish stable suspension of sub-micron magnesium dust in gas oil with a 64% (weight) of solid. The organometallic one is a low viscosity brownish-gray liquid formed by an optimum blend of surface-active combustion catalysts based on metals in distillated petroleum. It has been experimentally proved that to obtain the best results, an optimal additive rate has to be adjusted. The dosage for both the slurry and the organometallic additives was calculated following a stoichiometric analysis between fuel oil flow and its percentage content of vanadium, sulfur and oxygen in gases, accordingly to the additive manufacturer recommendations. For the slurry-type additive, a proportion of 1 liter of additive for 3.8 tons of fuel oil with a magnesium-to-vanadium ratio (R) of 0.5, and 1 l of additive for each 1.8 t of petroleum for $R = 1$ was established. A fixed ratio of 1 l of organometallic additive for 3.8 t of fuel oil was also adjusted. The additive feeding point was located in the fuel pipe before the fuel oil heater, just after the filters. Physical characterization of the additives using both infrared spectroscopy and gas chromatography is depicted in Table 3 of Ref. [5].

2.2- Experimental tests procedure

To study the influence of the additives on acid corrosion of the rotary continuous-regenerative air heater, both qualitative and quantitative analyses have been performed. First of all, the corrosion rate of probes (coupons) made of two different steels has been evaluated on the actual air heater corrosion conditions. Other relevant parameters, such as acid dewpoint temperature, rate of acid build-up, fly-ash acidity and SO_3 gas concentration, have also been measured to correlate their behavior to the acid corrosion from a qualitative description of the process. At the same time, concentrations of O_2, CO_2 and CO at the stack gases have also been measured with an ENERAC Pocket-100 combustion gas analyzer. Remaining parameters, such as metal and steam temperatures, steam flow and pressure, etc., have been simultaneously measured from the own boiler instrumentation. Finally, the effectiveness of the Mg-based additives has also been analyzed correlating the degree of fouling of the CRAHs with the pressure drop caused by the deposits growth. Absolute pressure and pressure drop have been measured with pressure transducers with a relative error of 0.02%. Temperatures have been measured using Ni-Cr thermocouples with a relative error of 0.001%.

2.2.1.- Determination of the corrosion rate

Despite the wide range of corrosion monitoring techniques (corrosion coupon, linear polarization, electrical resistance, among others), there is no standard or preferred way to perform corrosion tests [7,8]. Any of these monitoring techniques can only provide limited information, and in most practical applications, combinations of them are needed. In this research, the average corrosion rate has been quantitatively calculated measuring the weight loss of test samples (coupons) exposed to the actual atmosphere at the operational conditions. 48 rectangular coupons, 24 in each air heater, were randomly located in the baskets covering both cold and hot areas for all the experimental conditions. The coupons were made of two different materials, namely: a carbon steel (CT-3) and a corten® steel. The nominal composition of the two steels is presented in Table 1.

Table 1*. Chemical composition of the CT-3 carbon steel and the Corten® steel used in the coupons for corrosion rate calculation*

Element	**Carbon steel (CT-3)**	**Corten® steel**
C	0.1	0.12
Si	0.2	0.5
Mn	0.5	0.5
P	0.02	0.1
S	0.05	0.02
Cr	0.02	0.8
Ni	0.01	0.05
Cu	0.3	0.5

Corrosion rate (in *mm/year*) of the coupons can be calculated by

$$CR = \frac{\Delta P}{A\, t\, \rho_m} \tag{1}$$

where ΔP is the weight loss, A the total exposed metal area, t the exposition time and ρ_m the metal density. For the three experimental conditions considered (regular fuel oil without additive, heavy fuel oil mixed with the slurry-type additive and heavy fuel oil treated with the organometallic one), coupons were always exposed to the flue gases atmosphere during 7,344 hours, which corresponds to 306 days of continuous work of the boiler. The weight loss of the specimens, ΔP, has been measured with a precision balance (0.01 *mg*) and the exposed area of the coupons has been calculated by

$$A = 2\,l\,a + 2\,l\,e + 2\,e\,a - 2\pi\,r^2 + 2\pi\,r\,e \qquad [mm^2] \tag{2}$$

where *l*, *a* and *e* are the length, width and thickness (in *mm*) of the coupons, while *r* is the radius of the fixing hole. All these distances were measured with a slide gauge with a precision of 0.005 *mm*. Taking into account the fixed exposure time, the *SI* units for weight and distances, as well as an average density of the steel of 7.85 mg/mm^3, corrosion rate is calculated using the simplified equation,

$$CR = 0.152\,\frac{\Delta P}{A} \qquad [mm/year] \qquad (3)$$

Considering the errors in the direct measurement of each parameter, a maximum relative error of 0.0125% on the corrosion rate calculation can be expected.

2.2.2.- Qualitative evaluation of acid corrosion

To evaluate the acid corrosion from a qualitative viewpoint, direct measurements of some other related parameters have been performed. Acid dewpoint temperature (*ADT*) has been measured to analyze the acidity of the exhaust gases. Load, oxygen levels, sulfur and moisture contents of the fuel and boiler cleanliness are some parameters that will affect the *ADT*. Typical values of dew point temperature *ADT* at the exhaust gases when an untreated fuel oil is burned varies between 125°*C* and 150°*C*. It has been proved [9,10] that the most intense cold-end corrosion took place when the flue gases temperature ranged from 20°*C* to 30°*C* below the *ADT*. However, to know the actual corrosion degree of the condensed acid the *ADT* determination should also be complemented with the rate of acid liquid film build-up (*RBU*) on the metallic surfaces. The *RBU* is a direct indication of the acid condensation, and is correlated with the gas flow corrosion potentiality [9], so that the peak in the *RBU* curve fits the maximum of the corrosion rate. A moderate to intense cold-end corrosion should be expected for *RBU* values higher than 100 $\mu A/min$ [11]. These two parameters, acid dewpoint temperature (*ADT*) and rate of acid build-up (*RBU*) have been measured with a Model 220 portable Land Dewpoint meter. The probe was introduced into the duct through the gas sample port shown in Fig. 1 of Ref. [5].

Fly-ash acidity (*pH*) is another of the parameters selected to qualitatively evaluate the cold-end corrosion process. Fly-ash deposited on the continuous-regenerative air heater surfaces has been collected into four specially designed sheaths, and analyzed once per week. These collectors were placed just before and after both air heaters. Acidity of the wet fly-ash has been measured with a digital HI 9017 pH/mV/°C meter (Hanna Instruments, Bedfordshire, UK). Fly-ash composition was determined by electron micrograph analysis using image processing from scanning electron microscopy especially focused on the sulfur concentration. Concentration of sulfuric trioxide, SO_3, at the flue gas is another important parameter to be considered in cold-end corrosion. SO_3 concentration (ppm) has been measured using the condensation (hot water) method [12].

3.- RESULTS AND DISCUSSION

The continuous decrease of quality in the fuel oil burned in the power plant under study motivated a thorough control on the efficiency of the combustion process. The increase in asphaltene contents causes fuel oil instabilities [13], causing a reduction in combustion efficiency. The use of the combustion additives, mainly the organometallic one, has yielded an increase on the combustion efficiency due to the speed up of the combustion reaction, ensuring a complete combustion with low excess air and reducing stack heat loss. This behavior has been attributed to the surfactant effect of this oily additive, which reduces fuel oil surface tension, producing more uniform and smaller droplets.

3.1.- Qualitative analysis

All the experimental measurements have been performed for a fixed load of 330 *MW* established on the boiler. The addition of magnesium oxide-based additives to the fuel oil caused different cold-end corrosion characteristics compared to the regular fuel oil case due to the change in the conversion mechanism of SO_2 to SO_3. It should be pointed out that the engineers of the power plant feared dramatic corrosion damages if the heavy residual fuel oil was to be burned without any magnesium-based additive. For this reason, no results were obtained for this particular experimental condition.

The average of the measured O_2 (*%*), CO_2 (*%*), CO (*ppm*) and SO_3 (*ppm*) values at the stack gases for the three different experimental conditions are displayed in Table 2. As can be seen, the use of additives enables a reduction in the excess of air with, at least, a slight increase in the combustion efficiency, as well as a lower SO_3 concentration measured in the exhaust gases. The use of additives produces magnesium sulfates instead of vanadates, which together with ferric oxides are the main catalysts for the SO_3 formation, which, in turn, causes the cold- end corrosion [14]. For this reason, a chemical modification of the slag is obtained when the Mg-based additives are used. At the same time a reduction of the acid dewpoint temperature (*ADT*) has also been measured when the additives are mixed with the heavy fuel oil. The full set of

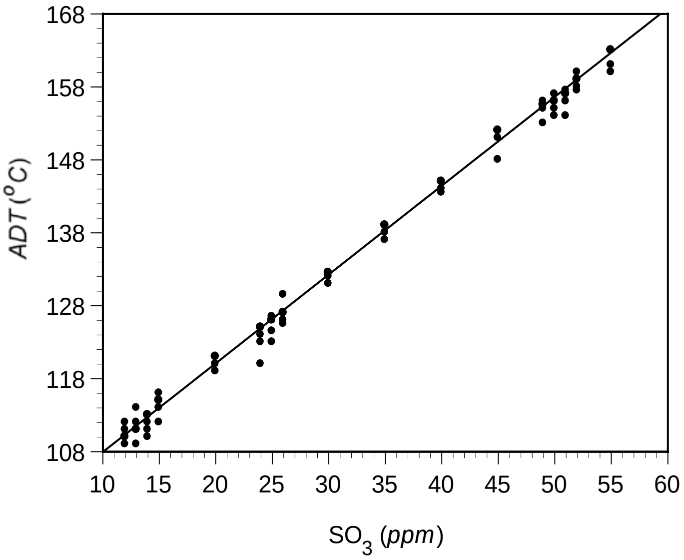
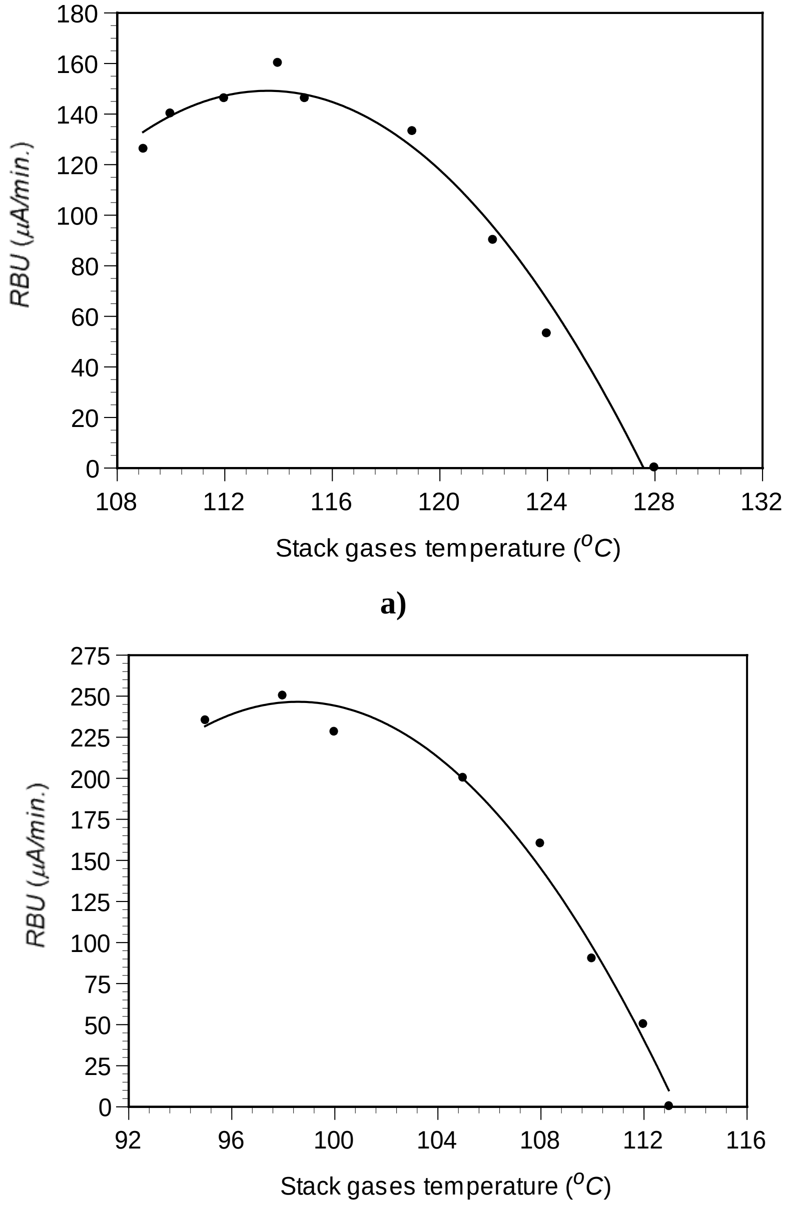


***Figure 1**. Linear correlation between SO_3 concentration and acid dewpoint temperature.*

measurements has been used to correlate the behavior of the acid dewpoint temperature as a function of the SO_3 concentration, and the results are displayed in Fig. 1. To ease the interpretation of the figure, only some experimental measurements are depicted jointly to the fitted curve. Strictly speaking, a linear correlation has been obtained, at least for the load used in these experimental conditions. The rate of acid liquid film build-up, *RBU*, is shown in Fig. 2. In Fig. 2a) the *RBU* measured for the regular fuel oil is depicted, while Fig. 2b) corresponds to heavy residual fuel oil mixed with the organometallic additive. Similar results as those previously discussed can be observed. The maximum corrosion potentiality corresponds to the range of flue gas temperature from 112°*C* to 114°*C* for the regular fuel oil, corresponding to the maximum of the curve around 160 *μA/min*. It is evidenced that the effect of the additive is to move the most dangerous zone (where largest acid condensation occurs) to lower temperatures (see Fig. 2b). When the organometallic additive is used, for an acid dewpoint temperature of 112 °*C* the *RBU* is around 50 *μA/min*, which corresponds to a 65% reduction. These results for *ADT* and *RBU* are very important because they imply that the stack gases temperature can be decreased without risks of acid corrosion damages and increasing the overall efficiency of the boiler due to a lower exhaust gases heat loss.

The acidity measurement (*pH*) did not show the expected conversion to a base-neutral fly-ash when using Mg-based additives. The *pH* of the fly-ash corresponding to the regular fuel oil condition yielded an average acid value of 2.5. However, the average values obtained when the heavy residual oil mixed with Mg-based additives was used were 3.4 and 4.9 for the slurry-type (*R*=0.5 and *R*=1) and 4.2 for the organometallic. These results would still indicate the presence



a)

b)

Figure 2*. Rate of acid liquid film build-up: (a) for regular fuel oil; (b) for heavy fuel oil with organometallic additive.*

of free acid in the fly-ash. A slight increase in the *pH* average value has been reached for the slurry-type additive when an Mg-to-V ratio R=1 is selected. However, the problems derived from the "mirror effect" deeply discussed in Ref. [5] (high levels of temperature detected in superheaters) limited the application of the R=1 ratio. In addition, chemical composition of some randomly collected samples of the additives-modified fly-ash, has also been determined using electron micrograph analysis. Even when the content of sulfur in the fuel oil composition was almost the same for all the experimental conditions (see Table 2 in Ref. [5]), results shown a large content of sulfur as the dominant compound in fly-ash for the organometallic additive modified samples. This result means that probably the ash has absorbed the sulfur released during fuel oil combustion, which is in good agreement with the reduction in SO_3 concentration measurement at the stack gases with Mg-based additives.

Table 2. *Measured values of O_2, CO_2, CO and SO_3 on the stack gases for the three different experimental conditions*

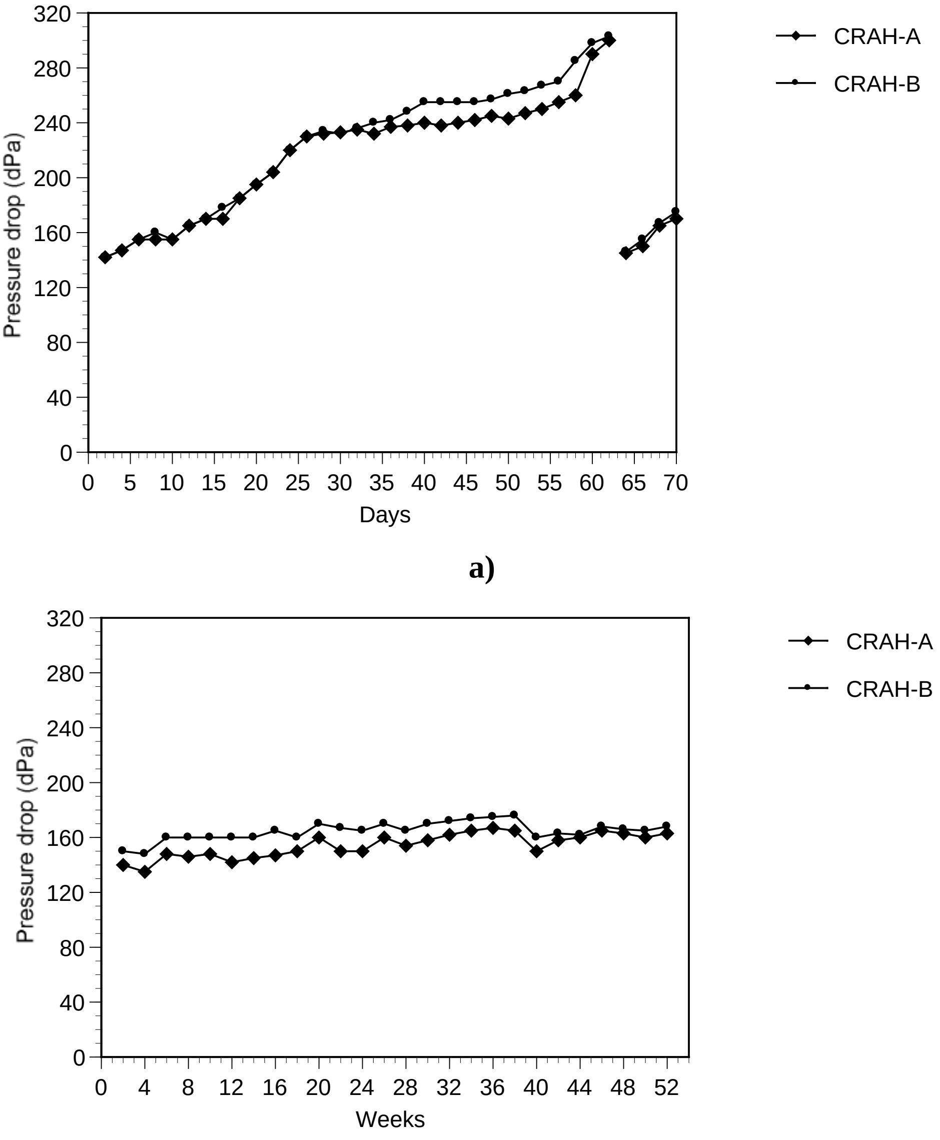
Parameters	**Regular fuel oil without additive**	**Heavy fuel oil with slurry-type additive**	**Heavy fuel oil with organometallic additive**
O_2 (*%*)	0.8	0.5	0.35
CO_2 (*%*)	15.5	15.5	15.7
CO (*ppm*)	35	258	275
SO_3 (*ppm*)	> 50	25	13.85
ADT (*°C*)	160	126	112

Acid dewpoint temperature (ADT) is also included in the last row.

The growth of deposits, and, therefore, the degree of fouling over the continuous-regenerative air heater has been evaluated measuring the pressure drop. According to the manufacturer recommendations, the best performance of this equipment is obtained for pressure drops lower than 250 *dPa*. In Fig 3 the measurement of the pressure drop in both air heaters is shown when the heavy fuel oil treated with the slurry-type additive for *R*=1 (a) and with the organometallic one (b), respectively, was used as fuel. Note that, due to the different behavior of the two additives, the divisions in the abscissa axis in Fig. 3a) correspond to “days” while in Fig. 3b) represent “weeks”. When the slurry-type additive was used an abrupt increase in the pressure drop was measured reaching values higher than 300 *dPa*. This periodic behavior has been observed every 55 to 65 days, forcing the cleaning of the CRAHs. However, after the cleaning process pressure drop started again to rise pointing to the increase of the fouling on the heat transfer surface. The same performance, has been observed for *R*=0.5, although not so markedly. On the contrary, a much steadier behavior has been obtained for the organometallic additive as can be observed in Fig. 3b). In this case, a roughly constant value of pressure drop around 160 *dPa* has been measured as an indicative of the improved ash composition conversion.

3.2.- Corrosion rate calculation

Following the methodology described in Section II.2.1, the corrosion rate of the coupons subjected to the actual stack gases condition has been calculated. Results obtained from the



a)

b)

Figure 3. *Behavior of the pressure drop in both air heaters when the heavy residual oil was used as fuel: (a) with slurry-type additive; (b) with organometallic additive.*

three experimental conditions are displayed in Table 3 for both CRAH A and B. Collection of corroded material from the coupons exposed after a mechanical cleaning has been performed following the standard normative ISO 8407:1991 [15]. As it will be demonstrated below, corrosion rate is mainly dependent on the mean temperature of the air heater metal surface. For this reason, to perform the appropriate analysis the CRAHs heat transfer surfaces have been divided into “hot-” and “cold-zones”.

A large difference of corrosion rate has been detected between cold and hot areas. However, an analysis of the results shows that the corrosion rate for both carbon and corten® steel are similar for all experimental conditions. Additionally, the corrosion rate in the metal surface of the cold-area at CRAH-A is bigger than that at CRAH-B. Probably this difference can be attributed to the aerodynamic design of the boiler, which displaces the combustion to the left part of the furnace.

Table 3. *Corrosion rates (mm/year) calculated for the three experimental conditions*

	Regular fuel oil		**Heavy fuel oil with slurry-type additive**		**Heavy fuel oil with organometallic additive**	
	Carbon steel	**Corten steel**	**Carbon steel**	**Corten steel**	**Carbon steel**	**Corten steel**
Cold area:						
CRAH-A	1.6729	1.6532	0.6269	0.6232	0.1393	0.1452
CRAH-B	0.5396	0.5401	0.1784	0.1744	0.0734	0.0873
Hot area:						
CRAH-A	0.02373	0.02341	0.02613	0.02924	0.01049	0.00993
CRAH-B	0.02934	0.0327	0.03984	0.05456	0.02939	0.02615

The previously commented difference of corrosion rate between cold and hot areas can be explained by the different average temperature of the flue gases and metal surface due to the heat exchange in both areas. It is important to keep in mind that the value of the surface element temperature in CRAHs is generally situated about halfway between those of the flue gas and cold-air. Measurements of the metal surface temperature are displayed in Table 4. As can be observed, the surface metal temperature of the pie-shaped baskets corresponding to the hot-area of both CRAHs has always been kept above the acid dewpoint temperature of flue gases (compares with *ADT* measurements displayed in the last row of Fig. 1 for each of the experimental conditions). On the contrary, in the case of the cold-area, for condition 1 (regular fuel oil) surface metal temperature falls 45°*C* below the *ADT*, causing a large corrosion in the coupons placed on this area. Even when the slurry-type additive was introduced in the treatment of the heavy fuel oil (experimental condition 2) a similar behavior was obtained, but obviously with a reduced efficiency. In this case, the difference in both *ADT* and metal surface temperature is just of 10°*C*. Only when introducing the organometallic additive in the heavy fuel oil treatment, the surface temperature in the pie-shaped basket corresponding to the cold-area has been kept above the acid dewpoint temperature. It is for this reason that the lower corrosion rate of the coupons corresponds to this experimental condition.

As a general feature, corrosion rate calculations are in good agreement with the measurements of the parameters selected in the qualitative analysis. Lower values of corrosion rate correspond to lower SO_3 concentrations in the stack gases. At the same time, the use of additives reduces the amount of air needed to achieve a complete combustion, yielding lower concentrations of SO_3 and V_2O_5, and, subsequently, both lower cold-end corrosion damages and higher overall boiler efficiency.

Table 4. *Average values of surface metal temperature (°C) for all experimental conditions in both cold- and hot- areas*

Experimental conditions	**CRAH-A**		**CRAH-B**	
	Hot-area	**Cold-area**	**Hot-area**	**Cold-area**
Regular fuel oil	294.0	114.2	292.6	110.3
Heavy fuel oil with slurry-type additive	302.8	115.9	303.4	116.1
Heavy fuel oil with organometallic additive	304.7	115.7	303.3	115.5

3.3.- Techno-economical analysis

A techno-economical analysis for the two additives tested has been performed taking into account the actual measured consumption and the specific costs for fuel oil and additives at the time of the experimental campaign. The overall analysis is based on the equation,

$$Z = G_{Add}\, P_{Add} + B\, P_{fo} \qquad [\$/year] \quad (4)$$

In this equation Z, P_{Add} and P_{fo} are the total annual cost for fuel oil and additives in *$/year* and the unitary prices for both additive (in *$/l*) and fuel oil (in *$/t*), respectively. G_{Add} is the annual consumption of additive in *l/year*, calculated by

$$G_{Add} = \frac{B}{R_{fa}} \qquad [l/year] \quad (5)$$

where R_{fa} means the fuel oil-to-additive ratio in *t/l* and B is the fuel oil consumption in *t/year*. Average prices of 125 *$/t* and 118 *$/t* have been considered for the regular fuel oil and the heavy residual oil during the period covered by this research.

In addition to the costs included in eq. (4) corresponding to the amount of fuel oil and additives used for steam generation, some other costs incurred both in CRAHs cleaning and maintenance processes have to be considered. In general, a pressurized solution of distillated water and caustic soda is normally used in the cleaning process to keep the pressure drop in CRAHs to the recommended value given by manufacturer. The required numbers of cleanings per year are mainly dependent on the experimental conditions. For example, when the regular fuel oil was burned, 3 cleanings per year were needed, 5 when the low-quality heavy fuel oil was mixed with the slurry-type additive, and no cleaning process was required during the experimental runs when the organometallic additive was used in the treatment. The extra cost due to distillated water and caustic soda consumption is taken into account in the equation

$$q_1 = \left(G_{dw}\,P_{dw} + G_{cs}\,P_{cs}\right) n_c \qquad [\$/year] \quad (6)$$

where, G_{dw} and G_{cs} are the amounts of distilled water and caustic soda used per cleaning (in *m³/cleaning*), n_c the number of cleaning and P_{dw} and P_{cs} their unitary prices, 0.40 $\$/m^3$ and 0.39 *$/kg*, respectively. Three hours and 120 m^3/hr of distilled water are needed to clean one of the continuous-regenerative air heaters, resulting in a total of 720 m^3 to clean the two CRAHs. 400 *kg* of caustic soda had to be added to the distilled water for each cleaning of the two CRAHs.

From a maintenance point of view, another extra costs due to manufacture and assembly/replacement of corroded pie-shaped baskets have also to be considered. These extra-costs are calculated with the equation

$$q_2 = \frac{\left(P_m + P_{ass}\right)}{UL} \qquad [\$/year] \quad (7)$$

where P_m and P_{ass} are the prices of both manufacture (254,045.6 *$*) and assembly or replacement (41,505 *$*) of one pie-shaped basket, and *UL* the useful lifetime (*year*) of the CRAHs elements. Obviously, different useful lifetimes have been estimated for the three experimental conditions taking into account the corrosion rate previously calculated. So, a useful lifetime of 1.5 *years* has been considered when the regular fuel oil was burned, 5 *years* for heavy fuel oil mixed with the slurry-type additive and 7 *years* when the organometallic additive was used in the heavy residual fuel oil treatment. Therefore, the total costs are calculated by the equation,

$$Q = Z + 445.87\, n_c + \frac{295{,}550.6}{UL} \qquad [\$/year] \quad (8)$$

Numerical results obtained from the above methodology are depicted in Table 5. Based on this analysis, it can be concluded that the use of a heavy fuel oil with additive is justified. Again, major savings have been obtained when using the organometallic additive, with a total saved amount of 2,880,335.83 *$* with respect to the regular fuel oil base-case.

***Table 5**. Comparative results obtained from the techno-economical analysis*

Parameters	**Regular fuel oil without additive**	**Heavy fuel oil**	
		Slurry-type additive	**Organometallic additive**
Total fuel oil consumption (*t/year*)	510,369.40	519,576.80	512,509.50
Cost including fuel oil and additives (*$/year*)	63,796,175.00	62,709,802.00	61,110,019.00
Extra cost due to cleaning (*$/year*)	1,367.61	2,279.35	-
Extra cost due to maintenance (*$/year*)	197,033.73	59,110.12	4,221.51
TOTAL COSTS (*$/year*)	63,994,576.34	62,771,191.47	61,114,240.51
Savings respect to regular fuel oil (*$/year*)	–	1,223,384.87	2,880,335.83

4.- CONCLUSIONS

A wide experimental measurement campaign has been performed in an electric power plant to study corrosion problems in low-temperature areas of the high-capacity steam boiler derived from the use of a low-quality heavy residual oil as fuel. Three different experimental conditions have been considered in the analysis: a regular fuel oil without any additive, a heavy fuel oil mixed with a slurry-type additive and a heavy fuel oil treated with an organometallic additive. Unexpectedly, the highest value of corrosion rate on CRAHs was obtained when the regular fuel oil has been combusted. A very limited useful lifetime of 1.5 years of the pie-shaped baskets has been estimated from the experimental results. The use of a low-quality heavy fuel oil treated with magnesium-based additives reduced the corrosion rate on coupons of carbon and corten® steels used as sample probes. It was observed that when magnesium-based additives have been used, a slight increase on the overall boiler efficiency has also been obtained reducing both the excess of air and the SO_3 concentration in the flue gases. A linear correlation between SO_3 concentration and acid dewpoint temperature has also been demonstrated. However, the use of additives does not produce the expected acidity neutralization in the fly-ash.

The best results have been obtained when the heavy fuel oil was mixed with the organometallic additive. Based on the corrosion rate calculations, the useful lifetime of the baskets has been increased up to 7 years. For this experimental condition, a lower acid dewpoint temperature in the stack gases has been verified, as well as a lower fouling on the CRAHs. A roughly constant value of pressure drop of 160 *dPa* has been measured and no cleaning of the CRAHs heat transfer surfaces was needed during the whole experimental period when the organometallic additive was used in the treatment. At the same time, a slight increase in the combustion efficiency has also been detected when using the organometallic additive, attributed to the surfactant effect of its oily character. From the techno-economical analysis total saved amount of 2,880,335.83 *$* with respect to the regular fuel oil have been achieved.

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