

Increase in the boiler's performance in terms of the acid dew point temperature: Environmental advantages of replacing fuels

J.M. Blanco *, F. Peña

*Dpto. Máquinas y Motores Térmicos, Escuela Técnica Superior de Ingeniería, Universidad del País Vasco/E.H.U.,
Alameda de Urquijo s/n (48013) Bilbao, Spain*

Received 3 November 2006; accepted 1 June 2007
Available online 3 July 2007

Abstract

The aim of air pre-heaters is to raise the temperature of the combustion air in boilers, using heat recovered from the power plant combustion gases. On the one hand, this paper compares the effects of the acid dew point temperature (ADT) on pre-heaters in a reference thermal power plant for two types of fuel, “fuel No. 2” and “low sulphur fuel” respectively and on the other hand, it shows how a changeover to this latter fuel would increase the useful lifetime of this equipment, reducing this way cost of maintenance due to the considerable decrease in the area exposed to ADT with the subsequent increase in the boiler's performance.

© 2007 Elsevier Ltd. All rights reserved.

Keywords: Acid dew point; Pre-heaters; Low sulphur fuel

1. Introduction

When analyzing requirements for installation of a heat recovery device, specifically a boiler economizer, there are three important items that must be considered [1], namely

- the sulphur content of the fuel being burned,
- the amount of excess air in combustion and
- the temperature of the inlet feedwater.

Downstream of the economizer there is an air pre-heater, which is susceptible to acid dew point corrosion as the temperature of gases decreases through it. This is commonly a rotating regenerator (as the ones considered here) but may be another form of gas–gas heat exchangers.

Fuel oil contains the elements carbon and hydrogen but also a certain amount of sulphur. During the combustion process, these elements are rapidly oxidized and the sulphur present in the fuel, will be combined with oxygen to

form sulphur dioxide (SO_2) in a partial oxidation and sulphur trioxide (SO_3) in a full oxidation, respectively. It is the presence of these sulphur oxides (SO_x) in the flue gas that represents the largest potential cause for extra corrosion [2].

SO_2 , for example, will dissolve in any free moisture that may be present in the flue gas to form sulphurous acid (H_2SO_3) a powerful corrosive. Approximately 1–2% of the SO_2 is further oxidized into SO_3 . Which combined with superheated water vapour, forms sulphuric acid vapour (H_2SO_4).

This is the main reason why the “acid dew point temperature” (ADT) could be reached, as the SO_2 contained in combustion exhaust gases does not condense, except through dissolution in water [3]. Consequently, this can only occur at temperatures lower than the water dew point (referred to in some literature as “physical dew point temperature”), which is the result of partial steam pressure on combustion gases and is not therefore likely to occur at temperatures higher than 60 °C. In other words, there is a possibility of dissolving SO_2 in water, if use is made of the steam's latent heat of condensation contained in combustion gases [4].

* Corresponding author. Tel.: +34 946014250; fax: +34 946014283.
E-mail address: jesusmaria.blanco@ehu.es (J.M. Blanco).

Nomenclature

a	thermal diffusivity $\left(\frac{\lambda}{\rho \cdot c_p}\right)$ (m ² /s)
A	wave amplitude $\left((\theta_{\max} - \theta_{\text{av}}) \cdot e^{-x} \cdot \sqrt{\frac{\pi}{a \cdot T}}\right)$
ADT	acid dew point temperature (°C)
CO ₂	carbon dioxide
c_p	specific heat at constant pressure
DG	dry gases
F	phase $\left(x \cdot \sqrt{\frac{\pi}{a \cdot T}} - \frac{2\pi}{T} \cdot t\right)$
F_a	damping factor $\left(e^{-x} \cdot \sqrt{\frac{\pi}{a \cdot T}}\right)$
H ₂ SO ₃	sulphurous acid
H ₂ SO ₄	sulphuric acid
L	length (m)
LCV	lower calorific value (kJ/kg fuel)
m	mass (g)
M	molecular weight (g)
NO _x	nitrogen oxides
SO ₂	sulphur dioxide
[SO ₂] _m	sulphur dioxide mass concentration (g/N m ³)
[SO ₂] _v	sulphur dioxide volume concentration (ppm)
SO ₃	sulphur trioxide
SO _x	sulphur oxides
T	wave period
V	volume (N m ³)
x	distance from surface (mm)

Greek symbols

α	total rotation angle of the rotating regenerator (°)
α_1, α_2	sectors of baskets directly affected by ADT for “fuel No. 2” and “low sulphur fuel” (°)

λ	thermal conductivity of the baskets (W/mK)
ρ	density of the panels (kg/m ³)
Δ	incremental
Λ	wave length $(2 \cdot \sqrt{\pi \cdot a \cdot T})$
π	number Pi (3.141516)
θ	temperature (°C)

Subscripts

a	relative to air
av	relative to the average value
c, e	relative to the cold end temperature
F	relative to the fuel
g	relative to the exhaust gases
h,e	relative to the hot end temperature
i	relative to the inlet
LS	relative to low sulphur fuel
m	relative to mass
max	relative to a maximum value
o	relative to the outlet
s	relative to the surface
V	relative to volume

These condensations take place with concentrations of around 98% and in these circumstances are not very aggressive. However when boilers are shut down, the highly water-repellent H₂SO₄ adsorbs atmospheric water vapour and reaches concentrations of around 40%, whereupon it becomes especially aggressive with regard to any metal wall.

The amount of SO₃ formed depends on the actual combustion conditions, with the following factors having the greatest influence [5–8]:

- Increase in excess oxygen in combustion.
- Fall in flame temperature.
- Presence of catalysts (V₂O₅, etc.).

Clearly, the greater the mass composition of sulphur in the fuel, the greater the partial pressure of SO₃ will be in the combustion gases and, consequently, the temperature for the formation of the ADT will rise [9,10] and, therefore, for the same operating conditions, the area of the heater exposed to extra corrosion will also be greater.

On one hand, this paper compares the effects of ADT formation on rotating regenerators in a reference 377

MW thermal power plant, depending on the type of fuel used. The purpose of these regenerators is to increase the temperature of the air that will subsequently be burned in the power plant's boilers [11].

On the other hand, the fuel referred to as “fuel No. 2”, formerly used in Spanish thermal power plants, has a mass percentage of sulphur of around 2.9% whereas “low sulphur fuel” should have <1% (in fact, it tends to be around 0.7%). This paper also shows that replacement of “fuel No. 2” by “low sulphur fuel” will significantly reduce maintenance on the rotating regenerator, due to the considerable reduction in the area exposed to further corrosion, so there will even be a possibility of withdrawing a number of other air pre-heaters from service which, in view of the extra consumption of steam in the boiler, are used to increase the “cold end” temperature of the regenerator [12–14] with the subsequent improvement in boiler performance.

2. Description and methodology

Condensation of these above mentioned acid vapors from the flue gas is the result of the flue gas contact-

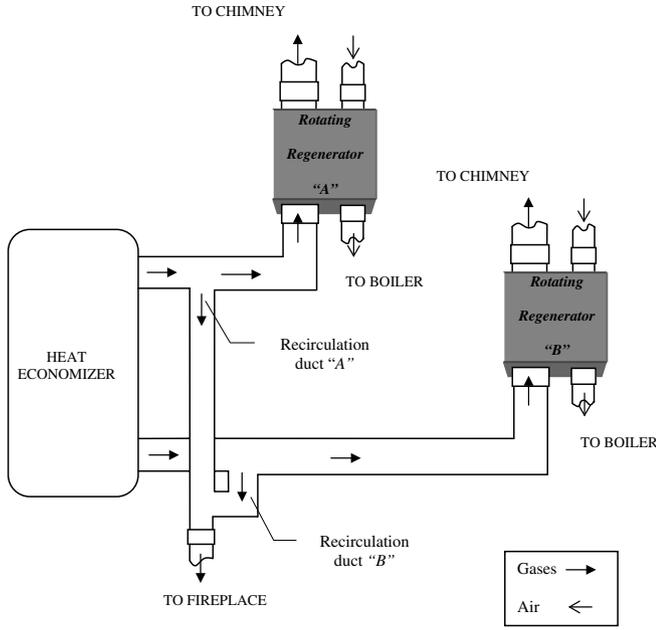


Fig. 1. Simplified layout of the rotating regenerator in the power plant.

ing the metal heating surfaces in the rotating regenerator unit.

The power plant of reference has two air pre-heaters of the rotary regenerative type, which receive the combustion gases from an economizer, as shown in the layout of Fig. 1.

The combustion gases pass through the metallic baskets (heat exchange panels), where they lose part of their sensible heat and the baskets, in turn, release the heat into the air in regular cycles of approximately 60 s. The air pre-heated in this way finally reaches the boiler where it is finally used as a combustion air.

The analysis method to be applied here, may be grouped into several stages

- Design of a new method for predicting ADT formation on rotating regenerators baskets, depending on the type of fuel used.
- Detailed analysis of the process of heat transfer inside a rotating regenerator.
- Appraisal of the sectors of the rotating regenerators baskets that are potentially exposed to the ADT for both “fuel No. 2” and “low sulphur fuel”, respectively.

3. Determination of the acid dew point temperature (ADT)

Fig. 2 has been obtained experimentally over the power plant of reference. It shows the formation of the ADT on the clean metal plate vs. the SO₃ concentration (ppm) in the combustion gases.

In the combustion of standard fuel-oils in Spanish power plants, the concentration of SO₃ in terms of volume in combustion products tends to be between 5 ppm and 25 ppm. By observing the ADT formation curve in the above figure, it can be seen that for a volume concentration

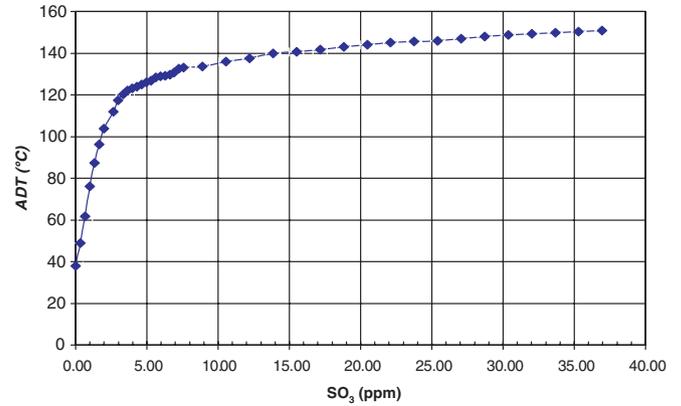


Fig. 2. Experimental curve of ADT (°C) vs. [SO₃]_v (ppm).

of SO₃ exceeding the value of 5 ppm the curve follows a logarithmic path. However, for lower values, the curve follows a parabolic path [15,16]. The salient data for “fuel No. 2” (LCV = 40,035.66 kJ/kg fuel) and “low sulphur fuel” (LCV = 40,630.68 kJ/kg fuel) are featured in Table 1 [17].

We now proceed to analyse what specifically occurs with the two above mentioned types of fuel.

3.1. Burning “fuel No. 2”

Via combustion calculations for our reference power plant, we have obtained both the mass and volume concentration of SO₂ in the combustion gases. Nevertheless, given that the gas analysers of the combustion gases do not provide mass results (they receive gases already cooled, so the analysis is performed on dry gases), this will be the basic value used for ensuring consistency with the data from the combustion gas detectors [18,19]. Thus

$$m_{\text{SO}_2(\text{DG})} : 0.0583 \text{ kg/kg F} \quad (1)$$

$$V_{\text{DG}} : 10.7928 \text{ N m}^3/\text{kg F} \quad (2)$$

$$[\text{SO}_2]_{\text{m}} \frac{0.0583}{10.7928} = 0.0054017 \text{ kg/N m}^3 = 5.402 \text{ mg/N m}^3 \quad (3)$$

It should be noted how SO_x emission values may be rigorously obtained by means of combustion calculations [20]. Anyway in this case, this calculation value has been compared with that provided by the combustion gas analyser in the power plant of reference and the result is very similar. This has enabled us to verify the analyser (correct siting of the probe, etc.).

Table 1

Typical mass composition of a “fuel No. 2” and “low sulphur fuel” and their main combustion reactions

% Mass	“fuel No. 2”	“low sulphur fuel”	Basic combustion reactions
C	85.40	85.98	C + O ₂ → CO ₂
H	10.38	10.91	H ₂ + 1/2O ₂ → H ₂ O
S	2.92	0.81	S + O ₂ → SO ₂
N	0.55	0.46	–
O	0.00	1.81	–
H ₂ O	0.45	0.00	–

In order to obtain the volume concentration (ppm), on the basis of mass concentration [21], the following expression is used (4), whereby (5):

$$\text{mg SO}_2/\text{Nm}^3 = \frac{\text{ppm} \times M_{\text{SO}_2}}{22.412} \quad (4)$$

$$[\text{SO}_2]_V : 1890 \text{ ppm} \quad (5)$$

Furthermore, considering that it has already been noted that SO_3 formation [22] amounts to 1% of the sulphur oxides (SO_x) formed in the combustion products

$$[\text{SO}_3]_V : 18.90 \text{ ppm} \quad (6)$$

As mentioned earlier, a correlation curve with a logarithmic trend has been obtained for values greater than 5 ppm, which provides the formation temperatures of ADT with greater accuracy than that achieved through Fig. 2. Fig. 3 is then obtained.

Finally, the logarithmic calculation expression gives the following equation:

$$\theta_{\text{ADT},1} = 12.065 \cdot \ln[\text{SO}_3]_V + 107.46 \quad (7)$$

By applying the value obtained in (6) to Eq. (7), the ADT finally obtained for “fuel No. 2” is

$$\theta_{\text{ADT},F \text{ No. } 2} = 142.92 \text{ }^\circ\text{C} \quad (8)$$

3.2. Burning “low sulphur fuel”

In this case, there are no analytical data on the mass concentration of SO_2 in dry combustion gases, because the relevant combustion calculations have not been carried out. However, we do have the value provided by the combustion gas analyser, which is acceptable, as its measurement results have been considered as validated, as mentioned above.

$$[\text{SO}_2]_m : 1300 \text{ mg}/\text{Nm}^3 \quad (9)$$

As seen in (4), this gives the following equation:

$$[\text{SO}_2]_V : 455 \text{ ppm} \quad (10)$$

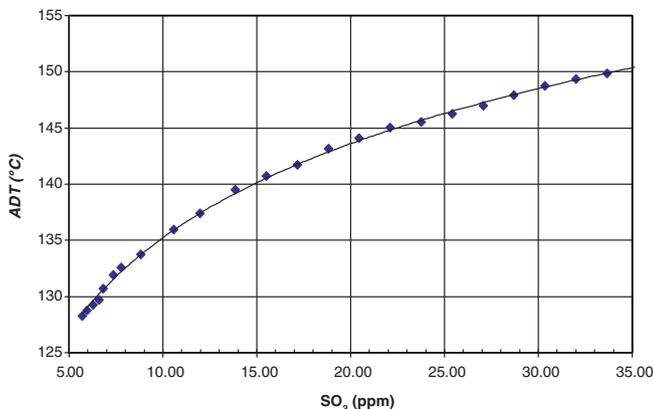


Fig. 3. Improved logarithmic curve of ADT (°C) for $[\text{SO}_3]_V < 5 \text{ ppm}$.

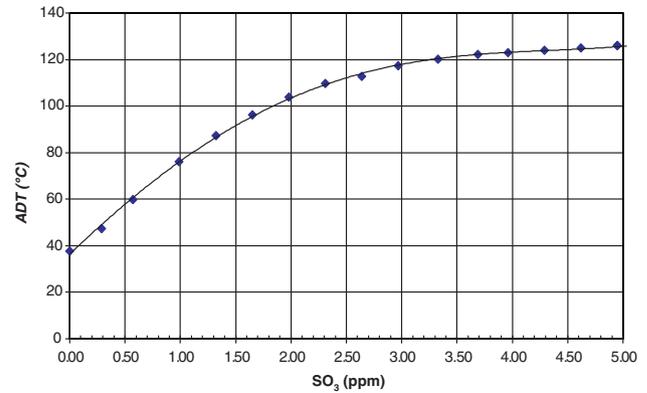


Fig. 4. Improved parabolic curve of ADT (°C) for $[\text{SO}_3]_V > 5 \text{ ppm}$.

If, as noted above, we consider that SO_3 accounts for 1% of the sulphur oxides (SO_x) formed in the combustion products. This gives

$$[\text{SO}_3]_V : 4.55 \text{ ppm} \quad (11)$$

As mentioned earlier, a parabolic correlation curve has been obtained for values below 5 ppm, which provides the formation of the ADT with greater accuracy than achieved through Fig. 2. We thus obtain Fig. 4.

The calculation expression finally obtained is the following equation:

$$\theta_{\text{ADT},2} = 0.1297 \cdot [\text{SO}_3]_V^4 - 0.7236 \cdot [\text{SO}_3]_V^3 - 5.2272 \cdot [\text{SO}_3]_V^2 + 45.912 \cdot [\text{SO}_3]_V + 36.269 \quad (12)$$

By applying the value obtained in (11) to Eq. (12), this finally gives the acid dew point temperature for “low sulphur fuel”:

$$\theta_{\text{ADT},LS} = 124.38 \text{ }^\circ\text{C} \quad (13)$$

4. Theoretical time dependent study of the heat transfer process inside the rotating regenerators

The heat transfer process between the air and gas zones in the regenerators (Ljungstrom type), details of which may be seen in Fig. 5, responds to the case of “walls subject to regular changes in surface temperatures” [23,24].

The time dependence temperature all over a plane within the wall (metal panels) can be deduced from Eq. (14), corresponding to one-dimensional conduction in transient state.

$$\frac{\partial \theta}{\partial t} = a \cdot \frac{\partial^2 \theta}{\partial x^2} \quad (14)$$

The solution of this differential equation provides the following expression (15) for the periodic time dependence temperature on a plane within the wall at a distance of x considering oscillation around an average temperature (θ_{av}) [25].

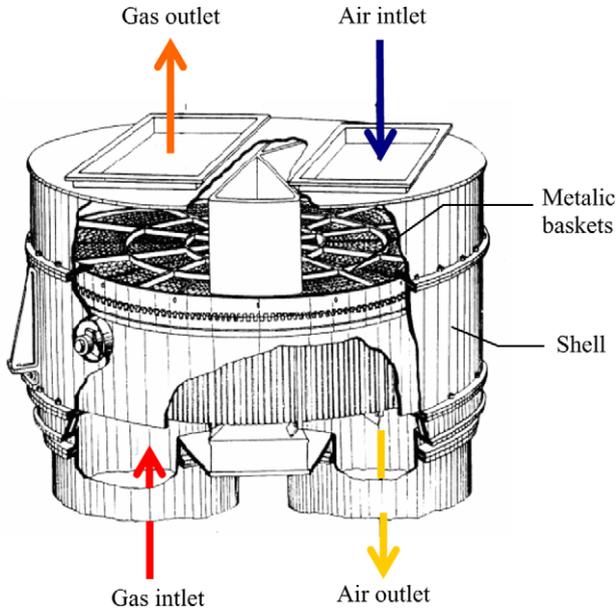


Fig. 5. Description of the heat transfer process inside a regenerator (Type “Ljungström”).

$$(\theta - \theta_m) = (\theta_{max} - \theta_{av}) \cdot e^{-x\sqrt{\frac{\pi}{aT}}} \cdot \cos \left[x \cdot \sqrt{\frac{\pi}{a \cdot T}} - \frac{2\pi}{T} \cdot t \right] \quad (15)$$

From this equation it is deduced, on the one hand, that at a specific moment the temperature distribution through the metallic walls depicts a sine wave that is exponentially absorbed and, on the other hand, that the temperature variation at a point inside the metallic walls presents the same

period (T) as on the surface, but its amplitude (A) decreases exponentially with the distance to the surface (x), as may be seen in Fig. 6.

The envelopment of all the families of curves presents an exponentially decreasing value with distance, as noted in the figure itself for a moment in time (t). In turn, as time elapses, the curve also alters in a sine-wave manner both on the surface, where the maximum values are located, and towards the inside of the piece, with a decrease in amplitude, as mentioned above.

5. Results and discussion

In practice, the trend in the surface temperature of the metallic panels that make up the baskets (heat transfer panels) on the air heaters is not a sine-wave function such as the one we have just addressed, but rather a parabolic-type function in heating and a logarithmic-type function in cooling, as may be seen in Fig. 7.

The mathematical expression that governs the temperature trend in the panels of the rotating regenerators cannot therefore be determined analytically. Nonetheless, empirically obtained calculation expressions exist that can do this.

The temperature of the panels on the heater baskets obviously cannot be measured directly either with thermocouples or with other direct contact devices, as the panels have a uniform circular movement [26,27]. Nevertheless, it can be ascertained with sufficient accuracy by means of the algebraic sum of the air and gas temperature readings on each side of the mechanical seals on the rotating regenerators, in the air outlet and combustion gases inlet zone

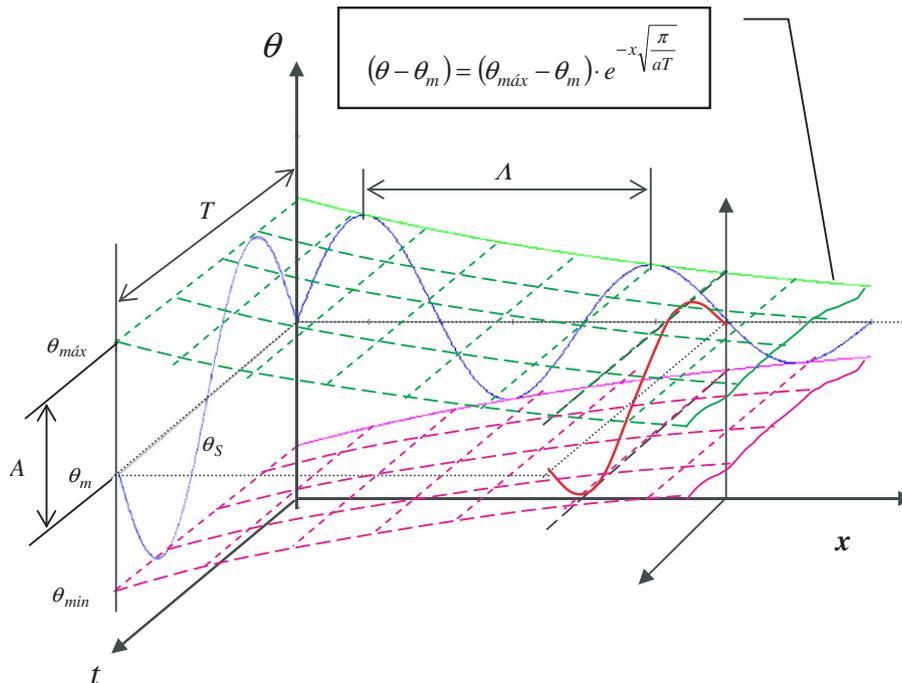


Fig. 6. Time dependent theoretical temperature field over the metallic baskets.

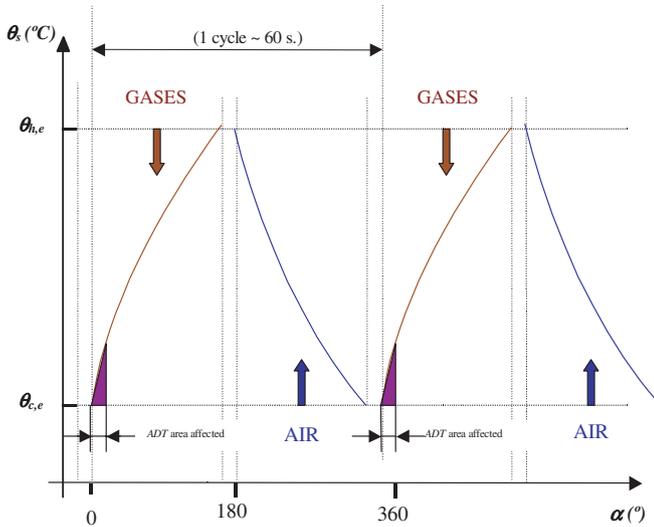


Fig. 7. Time dependent empirical surface temperature field over the metallic baskets.

that constitutes the lowest temperature area over the panels, referred to as the “cold end” temperature ($\theta_{c,e}$) [28], and on the combustion gases outlet and air inlet zone that records the highest temperature on the basket panels, known as the “hot end” temperature ($\theta_{h,e}$).

In this case, the aim is to obtain a “relative value” consisting of the difference between the figure for the sector of heater baskets exposed to ADT with “fuel No. 2” and the corresponding figure for the exposed sector with “low sulphur fuel” [13]. Consequently, no significant error is made if the temperature trend is considered “linear” in heating, which is the critical zone in the basket sector exposed to ADT. There follows a discussion of the results for each of the two fuels.

5.1. Identifying sectors exposed to ADT, burning “fuel No. 2”

The average measurements of a high number of temperature readings for the power plant of reference operating at full load with “fuel No. 2” provide the values which are used to obtain both temperatures $\theta_{c,e}$ and $\theta_{h,e}$, respectively, as it is shown in Table 2.

As previously seen in Fig. 7, the angle of rotation between the “cold end” temperature and the “hot end”

Table 2
“Cold end” and “hot end” temperatures for “fuel No. 2”, obtained from the power plant

“Fuel No. 2”	
Cold end values	Hot end values
$\theta_{a,i} = 43.0\text{ }^\circ\text{C}$	$\theta_{a,i} = 286.5\text{ }^\circ\text{C}$
$\theta_{g,o} = 156.5\text{ }^\circ\text{C}$	$\theta_{g,o} = 364.5\text{ }^\circ\text{C}$
$\theta_{c,e} = \frac{\theta_{a,i} + \theta_{g,o}}{2} = 99.75\text{ }^\circ\text{C}$	$\theta_{h,e} = \frac{\theta_{a,i} + \theta_{g,o}}{2} = 325.5\text{ }^\circ\text{C}$

temperature, without taking into account the mechanical seal zones that separate the air and gas zones, is $\alpha = 180^\circ$.

The temperature data on cold end and hot end obtained in the above mentioned table provide a temperature increase at the ends of

$$\Delta\theta_{(ends)} = (\theta_{h,e} - \theta_{c,e})_{FO\ No.\ 2} = 225.75\text{ }^\circ\text{C} \tag{16}$$

Furthermore, the difference between the formation of “ADT” and the “cold end” temperature is:

$$\Delta\theta_{(ADT-c,e)} = (\theta_{ADT} - \theta_{c,e})_{FO\ No.\ 2} = 43.17\text{ }^\circ\text{C} \tag{17}$$

These data have been used to consider a proportion by means of similar triangles, as shown in Fig. 8a.

Consequently, for the case of “fuel No. 2”, keeping the pre-heaters in service, the sector (α_1) of baskets exposed to ADT works out finally as follows:

$$\left\{ \frac{225.75\text{ }^\circ\text{C}}{43.17\text{ }^\circ\text{C}} = \frac{180^\circ}{\alpha_1} \right\} \Rightarrow \underline{\underline{\alpha_1 = 34.42^\circ}} \tag{18}$$

5.2. Identifying sectors exposed to ADT, burning “low sulphur fuel”

The average measurements of a high number of temperature readings for the power plant of reference operating at full capacity with “low sulphur fuel” provide the values shown in Table 3, which are used to obtain temperatures $\theta_{c,e}$ and $\theta_{h,e}$, respectively.

The temperature data on cold end and hot end obtained in the above table provide a temperature increase at the ends of

$$\Delta\theta_{(ends)} = (\theta_{h,e} - \theta_{c,e})_{LS\ FO} = 235.0\text{ }^\circ\text{C} \tag{19}$$

Furthermore, the difference between the temperature of formation of “ADT” and the “cold end” temperature is

$$\Delta\theta_{(ADT-c,e)} = (\theta_{ADT} - \theta_{c,e})_{LS\ FO} = 33.38\text{ }^\circ\text{C} \tag{20}$$

These data have been used to consider a proportion by means of similar triangles, as shown in Fig. 8b. Consequently, for the case of “low sulphur fuel”, keeping the

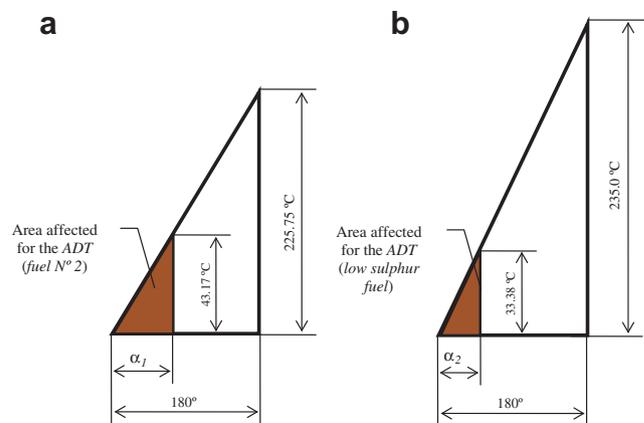


Fig. 8. Area of the baskets directly affected for the ADT; (a) burning “fuel No. 2”, (b) burning “low sulphur fuel”.

Table 3

“Cold end” and “hot end” temperatures for “low sulphur fuel”, obtained from the power plant

“Low sulphur fuel”	
Cold end values	Hot end values
$\theta_{a,i} = 32.5\text{ °C}$	$\theta_{a,i} = 287.0\text{ °C}$
$\theta_{g,o} = 149.5\text{ °C}$	$\theta_{g,o} = 365.0\text{ °C}$
$\theta_{c,e} = \frac{\theta_{a,i} + \theta_{g,o}}{2} = 91.0\text{ °C}$	$\theta_{h,e} = \frac{\theta_{a,i} + \theta_{g,o}}{2} = 326.0\text{ °C}$

pre-heaters in service, the sector (α_2) of baskets exposed to ADT works out finally as follows:

$$\left\{ \frac{235.0\text{ °C}}{33.38\text{ °C}} = \frac{180^\circ}{\alpha_2} \right\} \Rightarrow \underline{\underline{\alpha_2 = 25.56^\circ}} \quad (21)$$

Which is a lower value than the one obtained in the previous case. It means that replacing “fuel No. 2” with “low sulphur fuel” decreases the sector of baskets directly exposed to acid corrosion as has been demonstrated here.

6. Conclusions

From the above mentioned results, the following conclusions may be drawn:

1. A method has been designed for determining the acid dew point temperature of the baskets on rotating regenerative air pre-heaters in thermo-electric power plants through the use of data obtained in a power plant of reference.
2. On the basis of the empirical results of the ADT formation curve, it is noted that for a concentration of SO_3 exceeding 5 ppm in terms of volume, the best fit is a logarithmic equation, whereas for lower values it is closer to a parabolic shape.
3. An in-depth thermal analysis has been carried out on the transient process of heat exchange within a rotating regenerator, and a surface heating-cooling curve has been obtained that will serve as a basis for determining the sector of baskets potentially exposed to ADT.
4. Replacing fuel “fuel No. 2” with “low sulphur fuel” presents two key advantages: the saving of steam entailed by withdrawing from service the air pre-heaters’ steam generators, with the ensuing improvement in boiler performance, already contrasted which was carefully evaluated reaching values very close to 0.36%; and a considerable reduction in the sector of air heater baskets permanently exposed to ADT, which is around 8.86° , which represents a decrease in relative terms of almost 26%.
5. Bearing in mind that the manufacturer of the rotating regenerators recommends checking and replacing baskets every 4 years when burning “fuel No. 2”, the fact of replacing this fuel with “low sulphur fuel” would extend the maintenance time by around 1 year more, thereby leading to a considerable financial saving.
6. In addition to the above mentioned advantages, we should not ignore the environmental impact. Acid rain

is caused largely by the formation of nitrogen oxides (NO_x) and sulphur oxides (SO_x) produced by the burning of fossil fuels. The operating data provided by the gas analyser on the power plant combustion gases suggests that, as far as SO_2 emissions are concerned, burning “low sulphur fuel” results in reductions of more than 75% with regard to the same cycle scheme burning “fuel No. 2”.

7. Experimental values obtained for the power plant of reference are very close to the theoretical values given in this paper, so this has proven to be a very good method for measuring the environmental impact of these fuels.

Acknowledgement

Authors are deeply thankful to all staff of the power plant of reference for their help and facilities on the test experiments carried out.

References

- [1] S. Syri, N. Karvosenoja, A. Lehtilä, T. Laurila, V. Lindfors, J.-P. Tuovinen, Modeling the impacts of the Finnish climate strategy on air pollution, *Atmos. Environ.* 36 (2002) 3059–3069.
- [2] S. Syri, The impacts of climate change mitigation on air pollutant emissions. in: *Technology and Climate Change CLIMTECH 1999–2002; 14/2002 Final Report*, The Finnish National Technology Agency, Helsinki, Finland, 2002, pp. 224–233.
- [3] J.M. Beér, Combustion technology developments in power generation in response to environmental challenges, *Prog. Energy Combust. Sci.* 26 (2000) 301–327.
- [4] Y. Tan, M.A. Douglas, K.V. Thambimuthu, CO_2 capture using oxygen enhanced combustion strategies for natural gas power plants, *Fuel* 81 (2002) 1007–1016.
- [5] B. Bleckner, in: *26th Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, Pennsylvania, 1996, pp. 3231–3241.
- [6] N. Peters, *Turbulent Combustion*, Cambridge University Press, Cambridge, 1998.
- [7] M. Koebel, M. Elsener, Thermal optimization of boilers, *Chem. Eng. Sci.* 53 (4) (1998) 6657–6663.
- [8] A. Nordin, L. Eriksson, M. Ohman, Comparative analysis of cost of energy, *Fuel* 74 (1) (1995) 128.
- [9] Y. Hu, S. Naito, N. Kobayashi, M. Hasatani, CO_2 , NO_x and SO_2 emissions from the combustion of coal with high oxygen concentration gases, *Fuel* 79 (15) (2000) 1925–1932.
- [10] G. Nunnari, S. Dorling, U. Schlink, G. Cawley, R. Foxall, T. Chatterton, Modelling SO_2 concentration at a point with statistical approaches, *Environ. Model Soft* 19 (10) (2004) 887–905.
- [11] A. Bejan, G. Tsatsaronis, M. Moran, *Thermal Design and Optimization*, John Wiley & Sons, Inc., New York, 1996.
- [12] J. Barroso, F. Barreras, J. Ballester, Behavior of a high-capacity steam boiler using heavy fuel oil: Part I. High-temperature corrosion, *Fuel Process. Technol.* 86 (2003) 89–105.
- [13] F. Barreras, J. Barroso, Behavior of a high-capacity steam boiler using heavy fuel oil Part II: Cold-end corrosion, *Fuel Process. Technol.* 86 (2004) 107–121.
- [14] B.W. Harris, Conversion of sulfur dioxide to sulfur trioxide in gas turbine exhaust, *J. Eng. Gas Turbine Power* 112 (1990) 585–589.
- [15] INTERBULL, Genetic correlation estimation procedure. <http://www-interbull.slu.se/documents/Genetic_correlation_estimation_procedure.pdf>, (Accessed January 3, 2005).
- [16] K. Meyer, M. Kirkpatrick, Restricted maximum likelihood estimation of genetic principal components and smoothed covariance matrices, *Genet. Sel. Evol.* 37 (2005) 1–30;

- W.S. Cleveland, Robust locally weighted regression and smoothing scatterplots, *J. Am. Stat. Assoc.* 74 (368) (1979) 829–836.
- [17] A. Demirbas, Calculation of higher heating values of biomass fuels, *Fuel* 76 (1997) 431–434.
- [18] B.G. Lipták, *Process Measurements and Analysis*, Third ed., Instruments Engineers Handbook, Chilton Book Co., Pennsylvania, USA, 1995.
- [19] G.H. Aylward, T.J.V. Findlay, *SI Chemical Data*, third ed., Wiley, New York, 1994.
- [20] J.M. Blanco, F. Mendía, F. Peña, Comparative analysis of CO₂ and SO₂ emissions between combined and conventional cycles with natural gas and fuel oil consumption over the Spanish thermal power plants, *Fuel* 85 (2006) 1280–1285.
- [21] J. Warnatz, U. Maas, R.W. Dibble, *Combustion*, third ed., Springer, Heidelberg, 2001.
- [22] S.C. Hunters, Formation of SO₃ in gas turbines, *J. Eng. Power* 104 (1998) 44–51.
- [23] A.F. Mills, *Heat Transfer*, second ed., University of California, Los Angeles, California, 1999.
- [24] W.F. Santos, J.S. Trábelo, Transient conjugated forced convection in a parallel plate duct with convection from the ambient and periodic variation of inlet temperature, *Appl. Sci. Res.* 51 (3) (1993) 625–638.
- [25] W. Li, K. Sadik, Unsteady thermal entrance heat transfer in laminar with a periodic variation inlet temperature, *Int. J. Heat Mass Transfer* 34 (10) (1991) 2581–2592.
- [26] G.P. Celata, V.P. Carey, Heat transfer and transport phenomena in microscale, in: *Proceedings of the International Conference on Heat Transfer*, 2005, pp. 115–123.
- [27] E.K. Zarifteh, H.M. Soliman, A.C. Trupp, The combined effect of wall and fluid axial conduction on laminar heat transfer in circular tubes, *Heat Transfer* 4 (1982) 131–135.
- [28] Variable sector plate quad sector air preheater, US Patent, Issued on June 29, 1999.