Steam generator performance by means of over fire air and reburning techniques

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***Abstract*—In the present paper. a mathematical model of a combustion steam generator is presented. The model of power plant was implemented using GE GateCycle code. The effects of Over Fire Air and Reburning combustion techniques on the plant performance were studied using from both theoretical and experimental approach. Experimental data were studied and represented depending on the combustion parameters. Moreover. a numerical model of the steam generator and of the power plant was developed in order to predict the global plant performance. Simulation results of showed a good accuracy between experimental and theoretical data particularly in terms of reduction of thermal specific fuel consumption.**

***Index Terms*—Over Fire Air, Reburning, Steam generators, Power Plants. Overall Efficiency.**

I. Introduction

In order to reduce NOx emissions by fuel oil fed steam generators in power plants a strong combustion control through combustion modification process is needed. Among all the possible technologies Over Fire Air (OFA) and Reburning (RB) have proved to be an effective way on NOx emission reducing method. According to these methods part of the fuel and combustion air are added separately into the post flame region instead of the main combustion zone. Thus. a three stages combustion process is realized [1]–[3]. In RB zone a part of Flue Gas Recirculation (FGR) is injected with reburning fuel (thermal power ratio in the range 5 to 20) to form a stage (second stage) characterised by rich mixture [4]–[6].

In the RB zone downstream the combustion zone. post combustion air is added to complete the main combustion. The main difference between staged combustion (OFA) [7]–[9] and Reburning is related to the different local stoichiometries that is possible to achieve in the furnace with the two techniques [10]–[12]. According to this method. most of the fuel is burned with a stoichiometric fuel to air ratio. in the main burner zone. favours differently from OFA. the presence of uniformly dispersed O2 entering the reburn zone [13]–[15]. The presence of oxygen aids the decomposition of HCN to NCO. that is one of the principal and limiting steps on its way to N_2 [16]–[18]. As drawbacks of the technique are the same of the staged combustion: the risk of corrosion in the reburning zone, due to the reducing conditions. becomes real if the fuel has high sulphur content [19], [20].

II. Nomenclature

m_1	Air flow rate main burners;
m_{1s}	Stoichiometries air flow rate main burners;
m_{RS}	Stoichiometries air flow rate main burners;
m_{OFA}	Air flow rate OFA;
m_{1fuel}	Fuel flow rate main burners;
m_{RBfuel}	Fuel flow rate main burners;
m_{fuel}	Total fuel flow rate;
i	Global excess air;
Q	Overall heat transferred to the water;
A_t	Total heat exchange area;
K_{rad}	Combined radiative and convective heat transfer coefficient;
s	Stefan-Boltzman Constant;
h	Convective film coefficient;
$T_{G,eff}$	Effective gas temperature;
$T_{W,eff}$	Effective wall temperature;
T_G, W	Arithmetic average of hot and cold temperatures;
ε_{GS}	Emissivity of gas suspension;
ε_{COAL}	Emissivity of coal particles;
ε_{OIL}	Emissivity of oil droplets;
ε_{SOOT}	Emissivity of soot;
ε_G	Emissivity of gas includig CO_2 and H_2O;
ε_W	Emissivity of the wall;
CS	Fraction of the cold surface area couled by water tubes;
$Gwgh$	Gas temperature weighting factor;
$Wwgh$	Wall temperature weighting factor;
$T_{G,Exit}$	Furnace exit temperature;
T_{adb}	Adiabatic flame temperature;
$T_{W,in}$	Wall (water/steam) inlet temperature;
$T_{W,out}$	Wall (water/steam) outlet temperature;
A_{corr}	Area correction factor;
G_{GRBF}	Recycle Gas injected from bottom of the furnace;
G_{GRRB}	Recycle Gas injected with Reburning fuel;
SH	Super-Heated (radiative);
SH-HT	Super-Heated high temperature (convective);
SH-LT	Super-Heated low temperature (convective);
RH	Reheated;
ECO	Economizer;

III. Reburning Method

The studied boiler is fed with fuel oil and/or natural gas, tangentially fired (according to Fig. 1) equipped with 20 burners located in 5 levels [21]–[23].

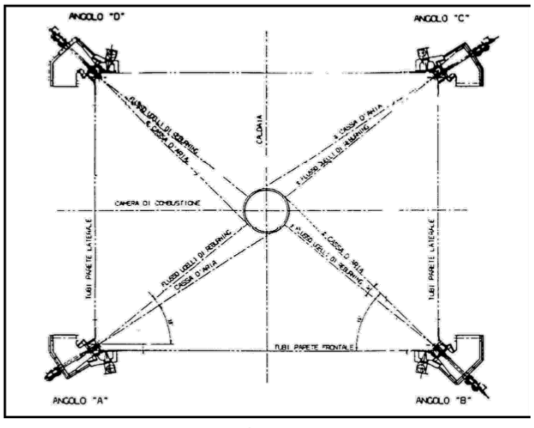

Fig. 1. Burner elevation setup.

The original configuration of the boiler was modified reducing the 5 burner levels to 4. Moreover. in the original fifth one burners were replaced by 4 fuel injectors [24]–[26]. OFA injection nozzles were installed in the upper part of the furnace located in the front and on the lateral surface of boiler following the disposition showed in Fig. 2.

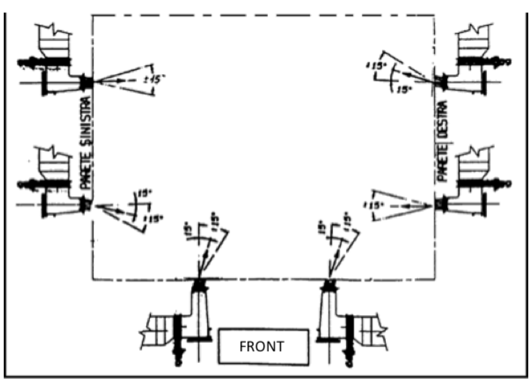

Fig. 2. OFA ports setup.

In order to provide the best configuration between the minimal interventions on the pressure parts and the respect of the chemical and physical limitations such as temperature profiles. the disposition of the reburning injectors and post-combustion air nozzles were selected accurately. FGR flow rate used to control the RH temperature. is injected from the bottom of the boiler. This fact has a great importance to further NOx emissions reduction [27]–[29]. In order to perform the injection of reburning fuel, the technique requires more recirculated gas flow rate than OFA. Thus. recirculation fans were replaced with more powerful ones because of the different running conditions.

IV. Mathematical Modelling

In order to study the effects of OFA and RB methods on steam generators efficiency. a mathematical model of the studied power plant was implemented within GE GateCycle environment. GE GateCycle is a computer program based on mass and energy balances that performs detailed steady state and off design analyses of thermal power station. As it is possible to see in Fig. 3. the mathematical model of power plant in the original configuration was tested using experimental data obtained during on design performance tests [30]–[34].

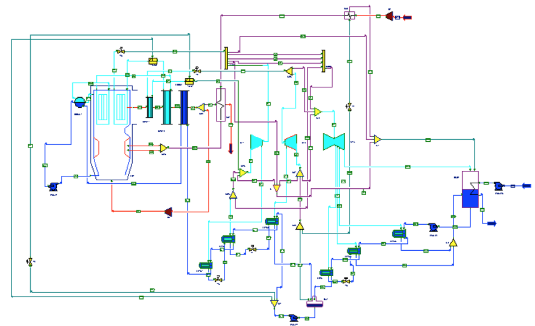

Fig. 3. OFA ports setup.

Combustion air for the steam generator equipment is split into both primary and secondary combustion air respectively. Two main configurations were analysed according to the same level of power plant (320 MW_e). The main operating parameters are the total fuel input, fuel mixture specification, reburning zone stoichiometry and excess air specification. The combustion chamber is divided into three regions in which RS1, RS2, RS3 (according to the definition RS3 includes RS2 and RS2 includes RS1 parameter) represent different parameters defined as in Eq. 1, 2 and 3.

$$RS_1 = \frac{m_1}{m_{1S}} \tag{1}$$

$$RS_2 = \frac{m_1}{m_{1S} + m_{RS}} \tag{2}$$

$$RS_3 = \frac{m_1 + m_{OFA}}{m_{1S} + m_{RS}} = i \tag{3}$$

Gibbs free energy minimisation of the constituents was used to calculate the exhaust gas composition. Radiation of gaseous combustion product such as H_2O and CO_2 is taken into account automatically using from Eq. 4 to Eq. 8.

$$Q = A_{corr} A_t K_{rad} (T^4_{G.eff} - T^4_{W.eff}) \tag{4}$$

$$K_{rad} = \frac{1}{\frac{1}{C_s \varepsilon_W} + \frac{1}{\varepsilon_{GS}} - 1} + \frac{C_s h}{4\sigma T^4_{W,eff}} \tag{5}$$

$$T_{G,eff} = G_{wgh} T_{G,exit} + (1 - G_{wgh}) T_{amb} \tag{6}$$

$$T_{W,eff} = W_{wgh} T_{W,exit} + (1 - W_{wgh}) T_{amb} \tag{7}$$

$$\varepsilon_{GS} = 1 - (1 - \varepsilon_G)(1 - \varepsilon_{soot})(1 - \varepsilon_{oil})(1 - \varepsilon_{coal}) \quad (8)$$

The analogy with Hottel model is evident. Thus. taking into account it. the evaluation of global emissivity of the exhaust gas was calculated with Eq. 9.

$$\varepsilon_G = \varepsilon_{CO_2} + \varepsilon_{H_2O} - \delta\varepsilon \quad (9)$$

Fig. 4, 5, 6 show the calculated fraction of heat absorbed by different sections of the boiler in function of combustion configuration according to several fuel mixtures.

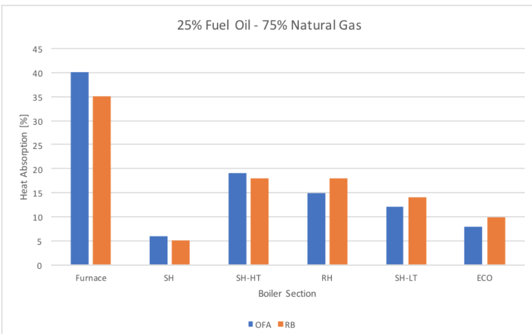

Fig. 4. Heat absorption in different boiler sections as a function of combustion configurations.

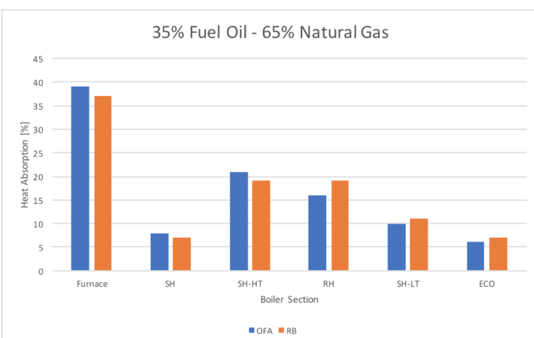

Fig. 5. Heat absorption in different boiler sections as a function of combustion configurations.

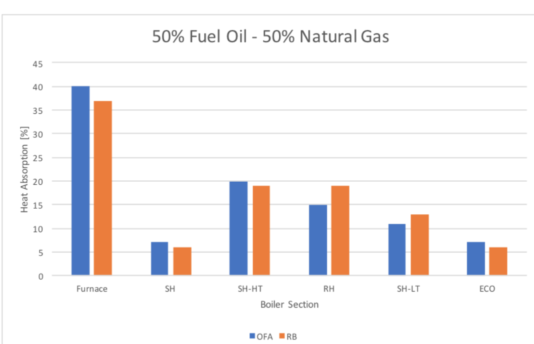

Fig. 6. Heat absorption in different boiler sections as a function of combustion configurations.

Efficiency of the steam generator and net cycle heat rate of plant have been calculated. Diagrams in Fig. 7 and 8 show these results as a function of fuel mixture.

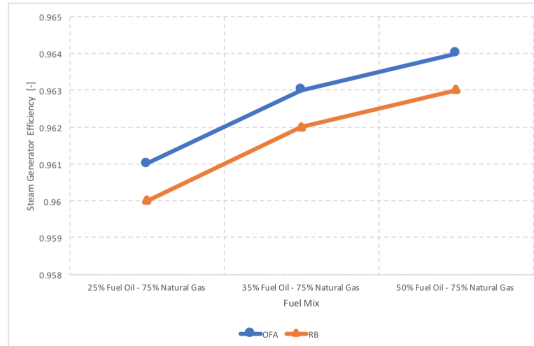

Fig. 7. Calculated Steam Generator Efficiency.

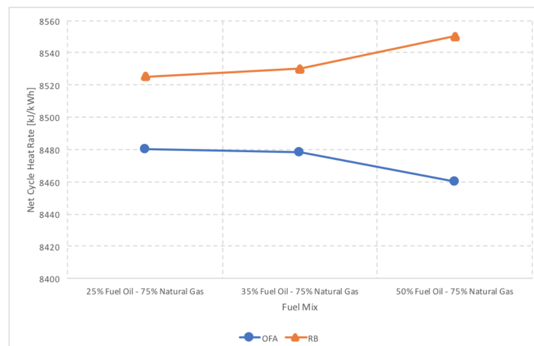

Fig. 8. Net Cycle Heat Rate as function of fuel mixtures and combustion configurations.

V. Experimental Analysis

One of the important aspects of a global evaluation of the Reburning technology is the analysis of the impact of this process on thermal performance [35]–[37].

For the complete characterisation of OFA and RB configurations more than 100 tests were carried out for a detailed evaluation of chemical and thermal boiler performance. In order to study the impact of the RB technique on thermal performance and pollutant emissions from the steam generator, OFA and OFA + RB tests were carried out using different oil and natural gas fuels mixture. In particular, 100%, 50%, 36%, and 25% fuel oil thermal power ratio were used during the tests.

Tests were conducted controlling the stoichiometry of the staged combustion in the three zones. In order to compare the two technologies, OFA and OFA + RB and study the effects on the boiler performances SH and RH water spray and boiler load were monitored. The exhaust gas was conditioned and analysed for CO, NO_x, O_2 and carbon particulate concentration. Test conditions are reported in the table reported from Fig. 9 to 13.

The pollutant emissions from the steam generator are reported in Fig. 14, 15, 16 and 17 in OFA configuration and

Test N.		29	35	40
Boiler Load		320MW	320MW	320MW
Combustion Technique		RB + OFA	OFA	OFA
% Methane (Thermal Power ratio)	0,00		0,64	0,52
% OFA		0,38	0,30	0,25
% REBURNING		0,09	0,00	0,00

Fig. 9.

Stoichiometries

Test N.		29	35	40
RS_1	-	0,805	0,755	0,872
RS_2	-	0,731	0,755	0,872
RS_3	-	1,188	1,08	1,16

Fig. 10.

Fuel

Test N.		29	35	40
Total Oil Flow Rate	Mg/h	67,3	25,3	32,9
Oil Flow Rate Reburning	Mg/h	6,2	0	0
Oil Flow Rate Main Burners	Mg/h	61,1	25,3	32,9
Total Methane Flow Rate	Nm^3/h	0	47,819	37,423
Methane Flow Rate Reburning	Nm^3/h	0	0	0
Methane Flow Rate Main Burners	Nm^3/h	0	47,819	37,423

Fig. 11.

Air - Gas

Test N.		29	35	40
Total Air Flow Rate	Mg/h	1079,2	1020,7	1063
Air Flow Rate OFA	Mg/h	415	307	264
Air Flow Rate Main Burners	Mg/h	738	793	799
Exhaust Gas Flow Rate Reburning	Mg/h	134	49	51

Fig. 12.

Water - Steam

Test N.		29	35	40
Steam Outlet Flow	Mg/h	1089	1068	1063
SH Water Spray Flow Rate	Mg/h	6	6	8
RH Water Spray Flow Rate	Mg/h	0	0	0

Fig. 13.

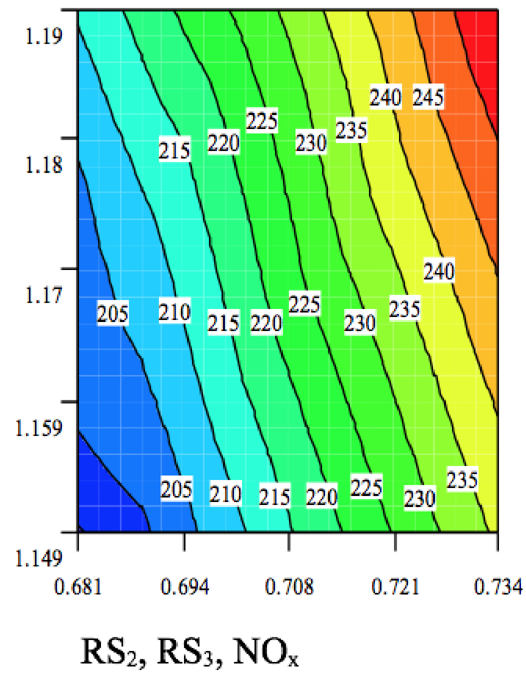

Fig. 14. NO_x ISO-Concentration maps in OFA configuration and 100% fuel oil.

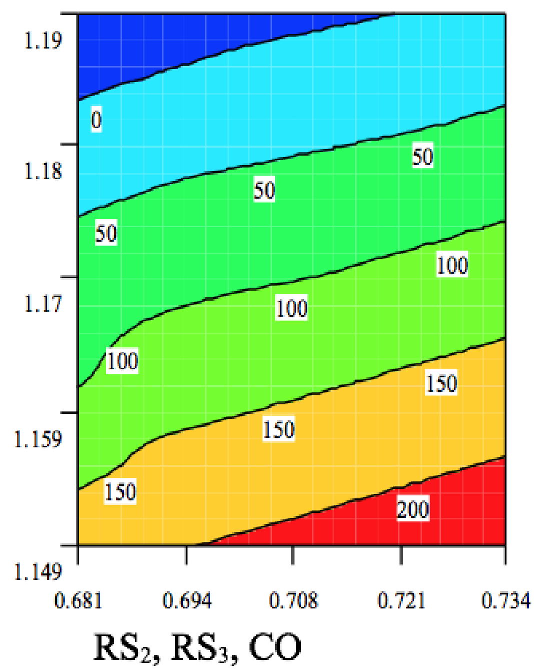

Fig. 15. CO ISO-Concentration maps in OFA configuration and 100% fuel oil.

100% fuel oil as well as 50% natural gas, respectively. While in Fig. 18 and 19 emissions from the steam generator in Reburning configuration and 100% fuel oil are reported.

VI. Conclusions

In the present paper, the effects of OFA and RB combustion techniques on emissions composition and on the overall efficiency of a steam generator were investigated. On the basis of theoretical and experimental results it is possible to conclude that:

1) Using OFA technique it is possible to maintain the control capacity of NO_x and CO concentration in exhausts when steam generator is fed with of fuel oil and natural

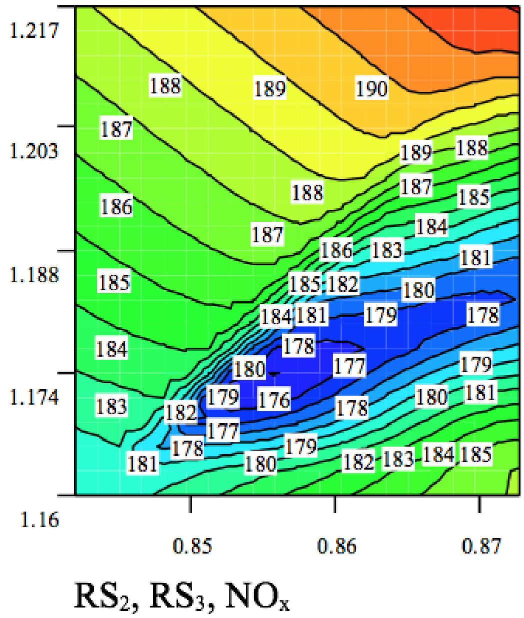

Fig. 16. NO_x ISO-Concentration maps in OFA configuration and 50% natural gas.

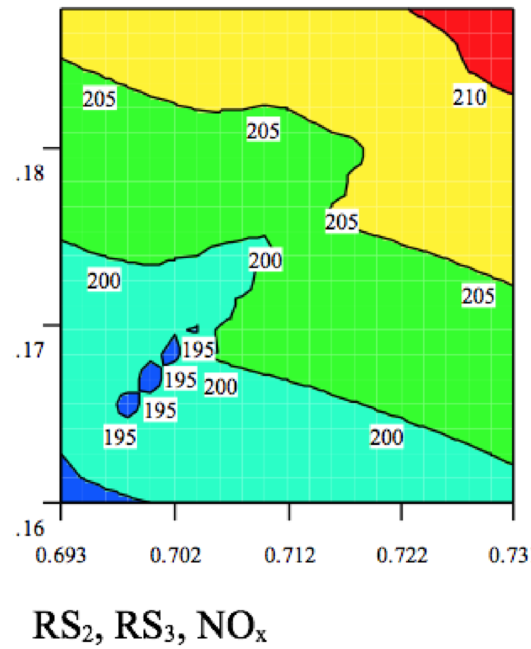

Fig. 18. NO_x ISO-Concentration maps in Reburning configuration and 100% fuel oil.

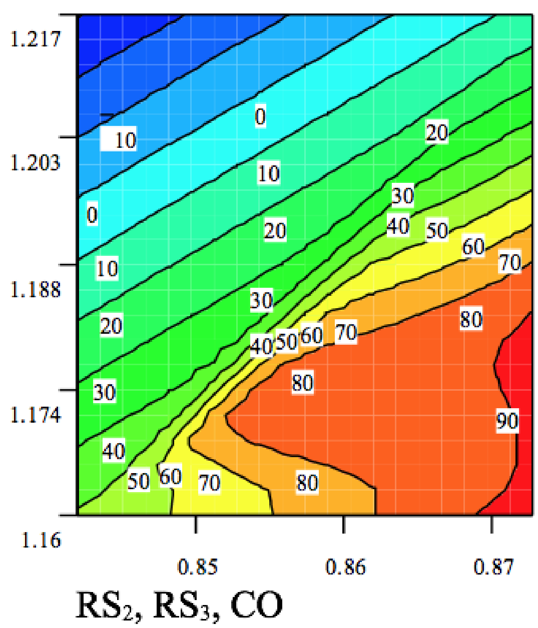

Fig. 17. CO ISO-Concentration maps in OFA configuration and 50% natural gas.

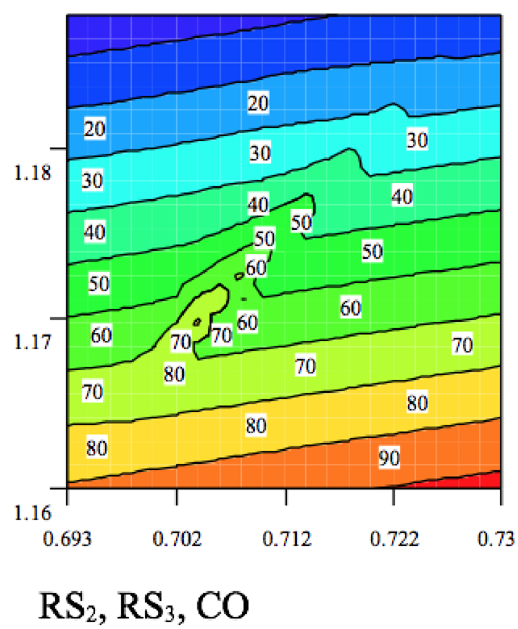

Fig. 19. CO ISO-Concentration maps in Reburning configuration and 100% fuel oil.

gas combination

2) If the fuel is exclusively oil (case total fuel oil), the use of RB technique becomes mandatory
3) Numerical model developed for steam generator and power plant has demonstrated a good accuracy in the comparison between experimental data and theoretical results carried out through several simulation tests with respect to thermodynamic state of steam and global plant efficiency
4) Numerical model developed for steam generator and power plant has demonstrated a good accuracy in the comparison between experimental data and theoretical results carried out through several simulation tests with respect to thermodynamic state of steam and global plant efficiency
5) Numeric analysis highlighted that a different distribution of heat absorption in the radiative and convective

zones of steam generator is obtained. In particular, OFA configuration allows radiative heat transfer while RB technique performs convective heat transfer.

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